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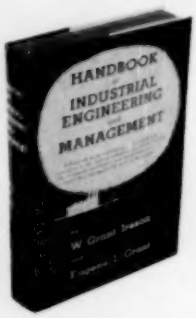

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PRESIDENT'S MESSAGE

D. G. Malcolm

It has been a real privilege as well as a distinct pleasure to serve A I I E during this past year, to visit with many of our fine chapters and universities throughout the country and to observe industrial engineers at work in many different and interesting types of activity. One is led forcibly to the conclusion that Industrial Engineering is becoming increasingly important in our American way of life.

The enthusiasm and efforts of members and officers in their work for our Institute should be mentioned. Progress which has been made over the past few years is clearly the result of unselfish service of many people. We may pause here briefly to examine some of our progress, assess our future problems and objectives and then gird ourselves with renewed vigor for continued efforts.

Our Institute has grown considerably in the year since last April. Total membership, including student members and affiliates is now in excess of 4,100, an increase in excess of 40%. There are 47 Senior Chapters throughout the country—an increase of well over 50% in chartered groups. The A I I E is unique among professional societies in that we have Senior International Chapters. Provision has been made to reflect difference in real wages and we are hopeful that in this way we will contribute to proficiency in Industrial Engineering on the international scene.

Such growth should be a real source of pride and satisfaction to the many individuals who have engaged in the many activities related to this growth.

The American Institute of Industrial Engineers has recently been elected an Associate Society of the Engineers Joint Council. More detailed discussion of the scope of the Council will be made by the Chairman of the Professional Relation Committee in the future. Industrial Engineers are thus beginning to assume responsibility in the overall engineering

(Continued on Page 28)

Employee Motivation Through Financial Means

By Phil Carroll,* Professional Engineer

All of you should be interested in a recent book entitled "No Sale—No Job" by Alexander Heron. It is an explanation of economics in simple terms. It explains where jobs come from. All the way through, Mr. Heron emphasizes that we provide more jobs only as we succeed in getting more and more satisfied customers. He stresses the fact that our customers are the people who provide all the money we operate with in industry.

In this book is one sentence that is a good starting point for our discussion. So I want to take as my text the 11th Chapter, 23rd verse from the book according to Alexander Heron, "What can be done to injure sales by raising the cost of the day's work too high can be done just as definitely and just as promptly by making the value of the day's work too low." (p.85)

Rephrasing this sentence to fit our subject, it could read as follows, "What can be done to injure sales by raising the wage rate of the day's work too high can be done just as definitely and just as promptly by making the productivity of the day's work too low."

THREE WAYS

From that point of view, we have several ways open to us. I'll not touch upon that of reducing wages. Yet, you have seen in some places recently where plants are trying to get back some of their customers by means of wage reductions.

There are four ways that I do want to discuss. These are:

1. *To hold wages and productivity where they are.* If we follow this course, we make no improvement in our standard of living.

2. *To raise wages and/or fringe issues and maintain productivity at the present rates.* That would give us more inflation and further reduce the value of our dollar of savings and pensions.

3. *To hold wages and raise productivity.* This course of action will improve our living standards.

4. *To raise earnings and raise productivity.* This is the course that I think we should follow. It has a doubling effect upon our American way of living.

*Author of "Timestudy For Cost Control," "How To Chart Timestudy Data," "How To Control Production Costs" and "Timestudy Fundamentals For Foremen."

WAGE INCENTIVES

To get this doubling effect, I recommend the use of wage incentives. With incentives you can increase earnings, raise production and lower costs. Wage incentive is the only device I know of that will do all three of these constructive things. But only certain incentives will do all three.

PROFIT SHARING

Take profit sharing as an example. Is that an incentive plan? The answer is "Yes," under some definitions and for some people. Suppose there are losses instead of profits. Where is the incentive under that condition?

Profits result from three factors. These are:

1. Prices—employees cannot do anything to change prices.
2. Volume—employees can rarely do much to alter volume.
3. Cost—employees can raise and lower costs.

As I see it, cost is the only factor in profits that the employees can work on. For that reason, I'm not in favor of profit sharing as an incentive plan.

Perhaps the most notable example of profit sharing cited frequently is that of Lincoln Electric Company of Cleveland. It is true that the employees do get almost as much added take home pay through a share of the profits as they get in regular earnings. But I interpret these extra earnings as double incentive. My reason is that the share paid to the people in the shop is based on their piece work earnings and suggestion awards.

PERCENT PLANS

Then there are other so-called incentive profit sharing plans. One type is based on a percent of the sales dollar. I think this is unsound because sales dollars vary greatly during boom times and depressions. They vary even more with relation to the work done as the material content of the sales dollar varies from one product to the next.

Another similar plan is based on the percent of cost or value added. One example I recall sets 24% as the employee's share. This is a negotiated percent.

Such plans have one twist to them that I am very much afraid of. My question is, "What happens to improvements?" Is the percent that purports to measure employee contribution altered to agree with the method and equipment changes? Do not such plans tend to maintain constant costs regardless of methods improvements? You can see that if the savings due to improvements are paid to the employees, the customer does not get his share. That brings us to the question, "How can you attract more customers with the same or higher prices?"

Despite the questions I raise, these plans have one important advantage. They provide incentives for most of the people. That means indirect people as well as the direct are on a form of incentive.

AVOID GROUPS

But all of these plans have one defect in common. They are group incentive plans. To my way of thinking, group incentives entail several weaknesses. I want to mention three. The first is that, usually, group incentives pay everyone in the group the same percent of incentive. I think that this method has a tendency to reduce everybody to mediocrity. This effect is a little like the income tax that destroys initiative.

The second defect, as I see it, is that group methods of work measurement tend to wash out the selection of people on the basis of skill and ability. In many instances, you would have only seniority to go by. This can have some serious defects. As an example, the September issue of FACTORY reports an arbitration decision to the effect that you cannot fire or transfer employees who passed tests when they were hired.

Along this line, I always like the comment I found in Mr. James F. Lincoln's book "Incentive Management" (p.59). There he says, "Since the average span of life is increasing rapidly, funerals do not occur nearly as often as they should for the best progress of most companies."

Then the third criticism I have of group methods of incentives is that it is contrary to the fundamental that built America. It is contrary to the theme we hear so frequently nowadays "recognition of the individual." It is contrary to the "urge to get ahead" in that the aggressive and progressive individual is held down to the average.

In my opinion, you cannot correct for these defects with any form of merit

rating. Without work measurement of individual performance, all you have to go by is the color of a person's necktie.

ENCOURAGE THE INDIVIDUAL

I believe that we need to encourage the individual "urge to get ahead." Others agree with me. Paul Hoffman says, "Our society is organized to promote conditions which challenge the individual to realize his capacities." James F. Lincoln says, "It is obvious that the Creator in giving to man such abilities expected them to be used." And a third, Lecomte Du Nouy says that this urge to get ahead is "the trait which above all others links man most clearly to the divine task of evolution."

Thus point No. 1 that I would make is to encourage each individual to do the best he can with his abilities.

WHAT DID HE DO?

If you agree, then how do we know what an individual contributes? We know that we cannot tell from sales dollar measures. Likewise, most of us know that pounds are no good as measures. In general, the more work we do to any basic material the less it weighs.

The actual costs of the work done are meaningless because most costs figures are not worth the paper they're written on. Actual costs are somewhat like budgets. They are based on the errors of past performances. In budgets, we have no measure of the work to be done for the dollars allowed. In addition, we have no count of how often the work is to be duplicated.

I think that industry needs measures of the work that people do. Also, I believe that the way to get the measures of work done is by means of sound timestudy. Right here is where we get our increases in productivity.

"MANAGEMENT ERRORS"

We find through good timestudy that there is a lot of wasted effort in industry. We find the things that interfere with production. I call these "management errors."

Some of the interferences you can eliminate. Some you can reduce. Some you would continue because it would cost too much to remove their causes.

These "management errors" are buried in all non-incentive operations. Often, these are hidden in the overall incentive plans. Actually, it is the reduction of these errors that is the source of part of the incentive payments made under the overall types of plans.

Point No. 2 then is let's measure the work a person does and separate the useful work from the management errors. More about management errors later.

SIMPLE INCENTIVES

Now, when we talk about timestudy-incentives, many people think of piece work. They think of simple incentives as a way to pay more money for more pieces. Some think that "more bucks" will cure anything.

Many managements I have known try to substitute timestudy-wage incentives for supervision. They try to use it to solve problems of reducing labor costs or opening up bottlenecks in production. Good timestudy-incentive will do these things. But I think the objectives are quite different.

To me, the thing that we are after is a measure of the so-called "fair day's work." What we need in industry is a measure of production—a common denominator to measure the output of mixed products. Also, we need a basis for proper costing. With this, we can find out where our profit leaks are. These facts you cannot get with the ordinary simple incentive plan.

Now the point that I want to make as No. 3 is that you need proper work measures in order to get correct costs.

WHAT IS COST?

Here you might think that I am getting off the track. To make sure that we are together, let's come back to "No Sale-No Job." In one place (p.83) Mr. Heron says, "The Employer acts as the agent for the worker in the task of selling the workers work for the customer dollars." In another place he says, "The basic task is to sell the work of every person who can contribute to the needs of consumers." (p.147)

Notice that Mr. Heron does not say that the employer is the agent to sell products. He makes no mention of toothpaste, automobiles, vitamin pills or suppositories. He omits all references to materials, chemicals, and drugs. He says to sell "work." This I call conversion.

CONVERSION

Conversion is what industry does. We convert some material we buy into the forms that our customers want. This is the work we do. And our overheads are related to this conversion. They are caused by the types of converting that we do.

I consider overhead to be a rental charge. It is the rent for the time that it takes to convert our materials into the finished products. Now we are back to time—the time of converting. This is what many folks call "labor." Some use the term labor cost or direct labor.

ACTUALS ARE WRONG

But labor cost can be very wrong as a measure of output. It mixes different wage rates. Then too, as you know, wage rates change every time the calendar turns a revolution. Besides as you also know, money does not measure value. It may include gross inefficiencies.

Actual time gets away from the variations in base rates. But it still includes all of the inefficiences. These two errors we can omit by using standard time.

When you have standard times that measure output, you can get correct overhead costs. And with correct timestudy, you can sort out "management errors." These are wasted time and effort. They are indirect labor and therefore cannot earn overhead.

This latter detail is very important to remember. Keep in mind that misapplied overhead costs creates two mistakes. When you overcharge one product you undercharge another. That is because we customarily spread overhead costs with a shovel.

MOTIVATION

But my subject is not costing. It is the motivation of employees. Here is the connection in a statement I found in AMA Management Review, April, 1954. "Not their products, not their trademarks, not their patents, not their plants and machinery, not even their organizations, are the greatest assets of our business enterprises. In a fundamental sense, the most valuable single asset of American business is *the responsiveness of the American people.*"

All of us like to compete. At some time or other we take part in foot races, baseball, tennis, football and golf. We get all worked up even as spectators. We avidly follow the sport page. At work, we compete against our fellow employees and those ahead of us in the line of promotion. And, all the time we are competing against ourselves. We repeatedly ask the question, "Are we getting ahead as fast as we should?"

I admit that "getting ahead" is too often measured in dollars. Nevertheless, the drive is there just the same.

SET STANDARDS

I'm convinced that either management sets standards of performance or the people set their own. My experience is that unmeasured work is about half of the "Standard fair day's work." Which do you want?

It's managements responsibilty to provide the jobs. They cannot do this except by selling the output. This you can do only if the price is acceptable.

Getting the volume is what Henry Ford did for us. He put America on wheels. His philosophy was to make automobiles for the multitude. He reduced prices repeatedly in order to bring the automobile within the range of most peoples' pocketbooks. Do you remember that a Ford once sold for $295? Certainly many of you remember what happened with cellophane.

PRODUCTIVITY

My experience is that people welcome standards to attain. I say this despite all the griping we hear. Most people want to do a fair day's work. They want to justify their employment and they seek protection against favoritism. They want a yardstick to measure by because they ask, "How am I doin'?"

Thus I believe that point No. 4 is to set standards for work performance so that people may measure themselves against them.

But if you have work standards only, many of your overhead costs are higher than they need be by 20 to 35 percent. The earnings of your people are 25 to 30 percent less than they could be. So

why not go a step further and provide financial incentives? Why not pay people more when they turn out more than the standard output? With the usual type of incentive plan, they can earn more than two 10 percent raises. They can add four or five 10 percent raises to their paychecks.

SUGGESTION PLAN

There is another financial motivation I think we should discuss. Why not have a highly successful suggestion plan? To be successful, I believe that a suggestion plan should pay more than the customary 10 percent award.

I do not know what the right answer is to, "How much more?" But the Lincoln Electric Company has had remarkable results with 50 percent of the net savings for one year. You might have better luck with 100 percent of net savings for a six months period.

My point is two fold, however. One is to get the employees to help maintain fair standards of work measurement. The other is to get the employees to help in the progress of the company. Remember "No Sale-No Job." Why not get them to protect their own job security.

Suggestions have paid off in Lincoln Electric. Their average rate of productivity increase from 1934 to 1950 was 15.35 percent as contrasted with all manufacturing in the same period with an average of 3.11 percent.

Thus I suggest that point No. 5 is to make it worthwhile for people to turn in their cost cutting ideas.

MORE MONEY

People want more money. They want higher standards of living. We create more and more desires with the billions we spend each year in advertising.

People are getting more money. They joined unions to help them get it. Unfortunately, much of the thinking is basic communism in that it seems directed at taking away from those who have to give to those who do not have. Then, too, we have tremendous pressures put on "ability to pay."

Where does this money come from? Some has come out of your profits. More may come from the same source because we cannot make progress by raising prices. Therefore the question is, "Can you afford to take less and less profits?" If the answer is "Yes," where will you get the money to expand? And you must expand to provide jobs for the increasing numbers of people.

For the reasons given I suggest that point No. 6 is to provide financial incentives so that people can raise their earnings as they apply themselves more diligently and skillfully.

SURVIVAL AND PROSPERITY

At this point I may startle you. I'm going to say that timestudy-incentives are only a means to an end. I think that you want to motivate employees for business reasons. Peter Drucker puts it this way in his new book "The Practice of Management" (p.63). "Objectives are needed in every area where performance and results directly and vitally affect the survival and prosperity of the business."

Your business survival and prosperity depend upon many things. Your employee's job security depends upon your survival and prosperity. We have said that we dare not price ourselves out of business. We have talked about needing profits for plowing back.

Now there are two other factors underlying survival and prosperity that I think should be mentioned. These are profit leaks and management predictions.

PROFIT LEAKS

Let's talk about profit leaks first. I've hinted at this one several times already when I mentioned "management errors." And I also said that we have misleading costs.

Behind the misleading costs is a basic fundamental. Mr. G. Charter Harrison, the inventor of standard cost, states it this way. "The outstanding defect of the conventional profit and loss statement is that it . . . reports profits *made* but it does not show profits *lost* . . . "Dead Hand of John Gough." (p.8)

My experience in a few metal working plants indicates that about 20 percent of their volume was sold at a loss. They were wrapping up ten dollar bills with each shipment. If we sell enough of that type of product we go broke.

Look at it this way. On the average profits run about 5.7 percent. Thus, when you plug a $5.70 cost leak someplace it is the same as selling $100 worth of goods to your customers.

To me this says, we should locate the profit leaks. We should find out where the money is made or lost. This requires that we get better costs than most plants have. Better costing requires better standards of performance.

PREDICTIONS

Now to the other factor of management. To me the biggest job that management has is to predict what will happen in the future. I call it crystal ball gazing.

Management has the eternal problem of deciding what about tomorrow. In the simple aspects, we have the problems of delivery promises to make and cost standards to meet. Further in the future are the questions about what new methods to install and what new equipment to buy. Still further out are decisions to make with respect to new sales territories to be opened up and new products to be developed.

Crystal ball gazing is the big management task. And the new-fangled operation research won't help very much unless we have better answers to put into the slot machine.

So it seems to me that you must get correct costs in order to guide your future planning. Right here is why you should want to motivate your people. I believe that you need to get them financially interested in making your guesses come true.

Nevertheless, I'm convinced that management must manage. To do that and to survive and prosper, you must control costs. You must know where your profit leaks are. You must average better than 51 percent in your crystal ball gazing decisions.

To do these things, you need better cost facts. Knowing your material cost is not enough. But that is all you know about cost unless you have work standards. Labor costs based on actuals are after the fact and they can be any amounts at all. In the same way, the overhead applied to such labor costs are equally unreliable. Remember that your manufacturing operation is a conversion process and that the costs of conversion are labor plus overhead.

WHAT IS A DAY'S WORK?

Now let's go a step further. To repeat Mr. Heron, "The employer acts as the agent for the worker in the task of selling the worker's work for the customer's dollars." Now what work is it that you must sell? How can you tell what it is without work standards? Will the work output be the same tomorrow as it was today?

Do you recall the text I started with? "What can be done to injure sales by raising the cost (wage rate) of the day's work too high can be done just as definitely and just as promptly by making the value (productivity) of the day's work too low."

Related to this is the question of union demands. These you may think of only in terms of money. Yet some plants have problems that relate to spreading the work and putting more people on the job.

WAGES

It seems to me that demands for *more* and *more* will continue. However, my experience is that it is not so much a question of what you pay as what you get for what you pay. If you pay a $1.00 an hour and get five pieces each one costs you 20 cents. If your wage rate is $1.50 and your production is ten pieces an hour your cost is 15 cents a piece. If your wages go up to $2.00 an hour and your production to twenty pieces, each one costs you 10 cents.

You have some controls on wages per hour. You have local, industry and national patterns. Many of you have job evaluation to help control the relations between hourly rates for comparable jobs. But what control do you have on output. What measures do you have of a fair day's work?

BETTER COST FACTS

Now please do not misunderstand my emphasis. Prejudiced as I am, I do not think that financial motivation is a cure-all.

LABOR INSIGNIFICANT

We can't duck the problem with, "Labor cost is only a minor item." Suppose

(Continued on Page 28)

A STATISTICAL MODEL FOR TIME STUDY*

H. P. Edmundson[1] and R. T. Nelson[2]

The purpose of this paper is to examine the basic concepts underlying time study methodology in order to develop a statistical model that is more realistic and more general. Time studies are carried out to determine fair performance time for a job. Any attempt to relate observed performance to a conceptual fair performance must necessarily involve some kind of performance rating procedure.

Performance rating is necessary only in studies which are to be used for determining what the workers *should be doing* rather than what they *are doing*. This is an important distinction; when it is desired to measure what is actually being done in the shop for scheduling or planning purposes, no speed rating of operators should be involved. However, when time standards are to be derived for wage incentive purposes, it is necessary to recognize the variation in the performance level of different operators on a job, and to arrive at some performance level within this range which is to be considered "normal."

Present Time Study Techniques

The rating method currently employed in time study is to multiply the operator's observed cycle time by a performance rating factor. However, this performance rating factor depends on the definition of normal performance for the job, which is measured by normal performance speed. A common definition[3] of normal performance speed for lower body motions is walking at three miles per hour, and of normal performance speed for upper body motions is dealing a deck of fifty-two playing cards into four separate piles in thirty seconds.

Most authorities assert that the bases of performance as defined above reflect a pace which can be sustained by a qualified operator. Time study men are trained to rate motion speed on other jobs as a percentage of these bases. Rating is the process during which the time study man compares the performance speed s of the operator under observation with the observer's own concept of normal performance speed s'.[4]

This rating procedure produces a percentage rating r of the performance of the operator observed during the time study,

$$r = \frac{s}{s'} . \qquad (1)$$

Multiplying the cycle time t by r gives the normal performance time t', i.e., the time that would have been observed if the operator had been performing at a "normal" performance level,

$$t' = rt . \qquad (2)$$

The standard operation time t" is obtained by multiplying the normal time t' by an appropriate allowance factor a which reflects expected delays extraneous or foreign to the performance cycle,

$$t'' = at' . \qquad (3)$$

The delay allowance factor a , necessary to adjust normal time to standard time, is obtained by one of the conventional methods such as a ratio-delay study. It should be noted that the current model as given by the above variables and equations is purely deterministic, rather than probabilistic, since all the quantities were considered as ordinary variables and not as chance or random variables.

Remarks

Some remarks will now be made concerning the current model and time study techniques in general.

The need for a new time study model becomes apparent if we examine the definition of rating and the definition of normal time which are given in the present model. Substitution of the definition of rating (1) in the definition of normal time (2) yields:

$$\frac{s}{s'} = \frac{t'}{t} . \qquad (4)$$

Hence this model yields a strictly inverse proportion between speed of motions and observed performance time. The incorrectness of this result is apparent when it is recognized, for example, that the leg motion speeds required by a short person and a tall person in order to walk three miles in one hour, will differ considerably, yet their accomplishments are the same.

If the present definitions of normal speed for upper and lower body movements are defined to be the *average* motion speed for adults walking at three miles per hour and dealing cards in thirty seconds, the motion speeds for an average adult will have been estimated. It is these average motion speeds that should be impressed upon time study men as they are trained to rate factory jobs.

To measure the mean height of all males over twenty-one years of age would be a practical impossibility. However, in any particular case, a reasonable estimate of such a mean could be made by measuring all available males over twenty-one years of age. In the same way, to find an average qualified operator for any job is a practical impossibility, but a reasonable result will be obtained if all qualified operators on the job are given equal consideration. The term "qualified" is used to signify all operators who have sufficient experience so that their learning curve has leveled off. Such a measure of average qualified operator is not only advantageous from a managerial standpoint in that it is readily available, but also from a general viewpoint in that it involves quantitative data from the very men on the job rather than an abstract, qualitative, concept of an average worker.

Proposed Statistical Model

Time studies are carried out to determine fair performance time for a job; or to express the idea in more concrete terms, *the average time that will be required by an average qualified operator to perform the job when working at a normal speed and using the standard method.*

Guided by this notion, we propose the following statistical model. For a given job and a standard method, both the speed-rating factor and the performance time will be conceived as chance or random variables, because they depend on chance events which occur at the various observation times. This is in contrast to the current deterministic model. Thus, r and t have a joint probability distribution. Moreover, we assume that this distribution depends on three parameters; p_1 the operator, p_2 the observer, and p_3 the observation time. First we will present some theoretical aspects of the statistical model, and then we will explain how it may be applied step by step. If the reader chooses to omit the mathematical theory, he may proceed

*This paper is a revision of earlier paper prepared while the authors were under contract to Logistics Branch, Office of Naval Research and employed on the Management Sciences Research Project at the University of California, Los Angeles.

[1]Mathematician, RAND Corporation, Santa Monica, California.

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[3]Barnes, Ralph M., **Motion and Time Study**, p. 353, John Wiley and Sons, New York, 1937.

[4]S.A.M. Committee on Rating of Time Studies, **Advanced Management**, Vol. 6, No. 3, p. 110, July-September, 1941.

directly to the technique which follows.

Theory

We will denote the joint probability density function of the random variables r and t by,

$$f(r, t; p_1, p_2, p_3). \quad (5)$$

However, we are really interested in the conditional probability distribution of t given r, i.e.

$$g(t \mid r; p_1, p_2, p_3) \quad (6)$$

since we want to know the theoretical regression curve of t on r. This curve is the locus of the conditional expected values of t given r, i.e.

$$E(t \mid r; p_1, p_2, p_3). \quad (7)$$

The intersection of the regression curve with the line $r = 1$ (normal speed) will give the expected performance time at normal speed,

$$E(t \mid 1; p_1, p_2, p_3). \quad (8)$$

The theoretical joint density function f is unknown, but it is estimated by an empirical density function, i.e., scatter diagram in the r-t plane. Since we want to estimate (8) for an average operator $\bar{p}_1$, an average observer $\bar{p}_2$, and a typical observation time $\bar{p}_3$, we must select p_1, p_2, and p_3 at random for each sample point of the scatter diagram.

Thus, the sample regression curve (least squares curve) of t on r estimates,

$$E(t \mid r, \bar{p}_1, \bar{p}_2, \bar{p}_3). \quad (9)$$

The intersection of the sample regression curve with the line $r=1$ estimates

$$E(t \mid 1, \bar{p}_1, \bar{p}_2, \bar{p}_3), \quad (10)$$

the theoretical mean performance time of an average operator using the standard method on the given job, when rated at normal speed by an average observer at a typical observation time.

Technique

In light of the preceding model we can statistically estimate the standard time as follows:

(1) Fix the job.

(2) Standardize the method.

(3) Select an operator, an observer, and an observation time at random, e.g., draw haphazardly out of three "hats." The operator should be qualified, and the choice of observation times should be as wide as possible.

(4) For this random combination of parameter values, record the sample point (r, t) of speed rating r and performance time t for a single cycle.

(5) Repeat steps (3) and (4) as many times as possible. A large number of points is desirable; more than fifty, say.

(6) Discard sample points for cycles containing foreign elements, i.e., elements which are not part of a regular work cycle, since they are accounted for later by the allowance factor.

(7) Plot the scatter diagram of the remaining n sample points, (r, t).

(Continued on Page 28)

Editorial Comments—

By R. N. Lehrer

SYSTEMS IN INDUSTRIAL ENGINEERING

Any profit-making concern has but two and only two objectives: *to make money* and *to make money*. These are two distinctly different objectives. First, the organization cannot long survive if it does not make money in short term operation. Secondly, it will not continue to survive unless it can continue to make money on a long run basis.

Now this is the very fundamental point so frequently overlooked by the Industrial Engineer and by management. We all understand what short term profits are and how we attempt to achieve them. But how do we go about insuring long term profits from our operations? We must first accept the fact that the two objectives are not the same and, in fact, frequently tend to be incompatible. Long term money is seriously affected by short term actions. We live to have our sins catch up with us.

Problems worked with today and solved by today's standards must also be solved by tomorrows standards. This requires thinking in terms of the "system" within which our immediate problems exist.

The basic philosophy behind Industrial Engineering is well stated by the old saw, "plan your work and work your plan." This is commonly thought of as planning and control by the Industrial Engineer. Within this frame of reference, the Industrial Engineer attempts to design an effective plan for accomplishing work, and to establish methods for evaluating the actual accomplishment relative to the designed-for and anticipated results.

This concept long ago gave rise to the time study work of Taylor, the methods study work of the Gilbreths, the planning work of Gantt, the control work of Emmerson, and on and on. But we have had some serious set-backs when "well conceived" plans failed to work—and we have been forced to recognize that it is essential to consider all factors that affect our plans. Our immediate problems are directly influenced by such usually overlooked factors as environment, other sections of the organization, the employees, the community, and society. All of these factors must be considered as a direct part of problems in addition to the more obvious short term cost values.

The Industrial Engineer, in most organizations, is intimately associated with change and improvement. More often than not, the Industrial Engineer is not only associated with change—he initiates change. But often, he refuses to accept changes that directly affect him. In fact, the Industrial Engineer has been conservative, and in some cases almost reactionary concerning his own work, methods and concepts. Smug complacency has resulted from ease of accomplishment in the performance of typical Industrial Engineering activities.

However, the situation is changing rapidly. At present, the Industrial Engineer is displaying an amazing adaptibility. This has not come easily; nevertheless, it is extremely encouraging and must be cultivated.

There are three main reasons for its development:

1. The Industrial Engineer has become aware of the necessity to think in terms of the "system" within which his problems exist.

2. The Industrial Engineer has remembered his engineering training.

3. The Industrial Engineer can foresee his own technological obsolescense unless he gets "the new look."

In a "systems" analysis, there are two groups of factors which must be considered of equal importance; the long term imponderables, and the direct, short term elements. It may be possible to reduce many of the individual items within each group and within the combination of the two groups to a common measurement basis. When this can be done, and it is extremely difficult to evaluate predicted effects in terms of present day dollars, we have a foundation for a true systems analysis. Endeavors of this sort are challenging the Industrial Engineer—he is meeting the challenge, for he is adaptable. I believe he will come up with many interesting and worthwhile problem answers as a direct result of thinking in terms of human systems and long term costs.

How to Invent a Profession

By Alvin Brown

Do you want to Do Things and Be Somebody? Do you want to Sublimate your knowledge and Rise Above the common level? Well, why not? You, too, can invent a profession. Just follow this blueprint:

1. Detect some phase of industrial operation that might be improved. This first step is easy. Industrial operators are human and have their share of human frailties. Moreover, they are usually anxious to improve their work, and therefore easily persuaded of their faults.

2. Attribute the fault to all industry. Don't say, Some companies could reduce their material costs, or, Some companies don't fix the responsibility for economy. Speak of the "comparative neglect of materials problems in the past" and say that "the engineers typically expect the buyers not to bother them."[1] Obviously, a fault shared by everyone can't be cured by mere urging to do a better job. It will be recognized that something drastic is called for. This is the cornerstone for a new department of knowledge.

3. Invent a name. Here we reach a highly critical step. Semantics is the handmaiden of this undertaking, but the name in particular demands a delicate touch. Avoid unfamiliar words; rather, seek a new combination of familiar words. Thus, "operations" and "research" are common-place separately, but together they achieve an esoteric quality. "Research" is a very dynamic word. No one will suspect that they mean merely the thinking a man ought to do about his job. "Value analysis" hasn't quite the same force, but yet it is an intriguing junction of two otherwise familiar words. "Mathematical programing" implies a world revolving in the perfect order of the sidereal system.

4. Invent a language. Here you face a real test of your ingenuity. All your work will be wasted if you can't rise above the common language of industry; the facade of novelty can crumble at a touch of the familiar. Don't say, Buy good enough materials at the best price, but instead, "In effect, the notion of highest quality as an absolute standard is rejected and replaced with a practical idea of the quality best suited for the price range and design problems of a particular company's products."[2] Don't say, by getting someone to do the details, an executive has more time to use his judgment; it is much more in keeping with the dignity of a new profession to say, "operations research will affect the executive's job by making him more conscious of intangibles. By presenting him with a comprehensive analysis of the quantitative factors it will focus his attention on those areas where his judgment is of prime importance."[3] Of course, you'll never speak of what makes a customer tick; you'll say, "when the scientist looks at these same figures, he seeks in them a clue to the fundamental behavior pattern of the customers."[4] And it just won't do to give each factor in a problem its proper weight; you must "combine and sublimate such otherwise inconsistent goals to a higher unified and consistent goal."[5]

5. There are, nevertheless, certain standard words that readers expect to find in literature of this character, without which you may not achieve a ring of true authenticity. Thus, you are expected to speak of "techniques" rather than methods, and if you feel obliged to use the latter term in any form, be sure you say "methodology." Then it is indispensable that you "integrate" something or somebody; you had best call your profession an "integrating process." Decisions must never be carried out; they must be "implemented." It will be good if you can work in "automation" somewhere and thus get the umbrella of the forward-looking who are no longer content merely to mechanize. If any of your ideas sounds a trifle weak, just say it is "practical;" that always convinces a business man. When anything needs to be adapted to something else, don't make the mistake of using that word; don't say "geared," either, for that will stamp you as just a little out of date; the only possible word today is "tailored."

6. Now you are ready to go to your public. And first, of course, you must tell them what your profession is. But be careful! It's not wise to give it too precise a definition. Don't be so incautious as to say, "In a larger sense, value analysis is just a special name for good procurement."[6] That would give you away. Besides, if you give a good broad definition, maybe it will cover some fields of activity you haven't thought of Try for an approach like this: "It is not our purpose to engage in any inconclusive battle over definitions of the concept."[7] If you can succeed in discussing your subject without telling anyone what it is, then you've nothing to worry about; you're in!

7. Next to the name, the most important thing is to convince people that this is no old stuff you are giving them. Grasp this nettle firmly. Fling it at them: "There is a new concept in management. It is called operations research."[8] "Mathematical programing is not just an improved way of getting certain jobs done. It is in every sense a *new* way."[9]

8. A touch of Gestalt won't do any harm. See if you can evolve something like this: "Operations are considered as an entity. The subject matter studied is not the equipment used, nor the morale of the participants, nor the physical properties of the output; it is the combination of these in total, as an economic process."[10]

9. You must let industrial managers know they are dumb, but this requires a deft touch, as you can imagine. You have to do this, because, if they aren't dumb, you can't make a case for taking over part of their job. But you can't let them know *how* dumb. So take it gently. By saying something like, "Many executives believe that a comprehensive, objective, quantitative analysis of the

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[1]Stanley S. Miller, "How to Get the Most Out of Value Analysis," **Harvard Business Review**, January-February, pp.123, 128.

[2]Miller, **ibid.**, p. 123

[3]John J. Caminer and Gerhard R. Andlinger, "Operations Research Roundup," **Harvard Business Review**, November-December 1954, p. 136.

[4]Cyril C. Hermann and John F. Magee, "Operations Research for Management," **Harvard Business Review**, July-August 1953, p. 101.

[5]Herrmann and Magee, **ibid.**, p. 106.

[6]Miller, **ibid.**, p. 131

[7]Caminer and Andlinger, **ibid.**, p. 132.

[8]Herrmann and Magee, **ibid.**, p. 100.

[9]Alexander Henderson and Robert Schlaifer, "Mathematical Programing," **Harvard Business Review**, May-June 1954, p. 73.

[10]Herrmann and Magee, **ibid.**, p. 101

factors affecting a major decision would be very useful to them,"[11] you can suggest to them that they have been underprivileged. Or perhaps you can flatter them a little (not too much) by pointing out how "the initiation of a value-analysis program depends on top management, and the continuing supervision of value is a top-management responsibility."[12] Top it off by admitting that your program will naturally have its greatest appeal to "soundly-managed companies."

10. Be modest about your accomplishments—but not too modest. Remember, as a scientist you are entitled to deference. Drop a name or two — nuclear physicists are good company to be in. This will let you take a lofty tone. "The scientific method, in its ideal form, calls for a rather special mental attitude, foremost in which is a reverence for facts."[13] Don't permit any inference that you would care to associate with lesser fry. "Operations research people are scientists, not experts."[14]

11. Now we come to the crux of our project. No door to this new profession must be left open to the uninitiated. Ordinary operating men mustn't get the idea that they can do the thinking about their problems. "Mathematical programming is not a patented cure-all which the business man can buy for a fixed price and put into operation with no further thought."[15] So you must say, "committees are most successful when they are supported by permanent groups to implement their decisions."[16] Or better still, just take it for granted that this will be an exclusive affair by a remark like this: "The O. R. team should be attached to the operating line in a staff capacity."[17]

12. Now for the final brick in your edifice. No one can be allowed to get the notion that this important work might occupy any menial position in the company structure, where jealous underlings might deflect your light. Now is the time to tell top executives that your place is right at their elbow, putting your hand to the same plow. "The O. R. team should not become a part of an existing service department," because the results of its thinking might get merged in factual (sic) investigations by other staff men. No, sir! "The O. R. team should be attached to a high level of management."[18] They may keep their titles and draw their salaries, but you'll be close at hand doing their thinking for them. "It must be established at least at a level where decisions can be made and where there is access to the executives."[19] *At least*, you understand!

[11] Caminer and Andlinger, **ibid.**, p. 136.
[12] Miller, **ibid.**, p. 125.
[13] Herrmann and Magee, **ibid.**, p. 101
[14] Herrmann and Magee, **ibid.**, p. 108
[15] Henderson and Schlaifer, **ibid.**, p. 75
[16] Miller, **Ibid.**, p. 131.
[17] Caminer and Andlinger, **ibid.**, p .133.
[18] Caminer and Andlinger, **ibid.**, p. 133.
[19] Herrmann and Magee, **ibid.**, p. 110.

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A Reply to Prof. Wayland P. Smith's Article

"Travel Charting—First Air for Plant Layout"

By James L. Lundy,

Instructor, University of Minnesota

Professor Smith's appreciation of travel charting as an analytical tool is no greater than mine. However, in his enthusiasm, Professor Smith has marred an otherwise informative presentation with the inclusion of one step which would make the travel chart lie to the unwary user. The problem arises in step 5.2 of the first example in which an attempt is made to calculate handling efficiency for a process layout.

In order to minimize the length of this discussion let us accept Mr. Smith's basic assumptions made in section 1. I point out that this is done for simplicity, (and Mr. Smith apparently had simplicity in mind in the origin of these assumptions) for the assumptions themselves could be subjected to considerable study and analysis. For example, wherein did the factor "twice" arise in the statement "Back-tracking will be considered *twice* as bad as moving work forward." Why not "three times" or "four times" or, better yet—why not equal? Is direction of movement so important in a process layout?

The important assumption is that the effectiveness of the layout is a function of the aggregate weights times distance. As Mr. Smith pointed out earlier in the article, some factor other than weight might be better for particular cases, but let us accept this as a valid assumption in light of the simplicity desired.

If we also assume (as Mr. Smith does) that the process sequences for individual parts are unalterable and that distances between work stations are equal, we are able to agree that 100 per cent efficiency in movement will be achieved when we minimize the sum of all weights x unit moves. A unit move is defined as a move between two adjacent work stations. A given weight going from A past B to C would thus accrue two unit moves. This 100 per cent efficiency value is 402.2 in the example given by Mr. Smith.

Smith's efficiency formula is

$$E \text{ (in per cent)} = \frac{402.2 \times 100}{X}$$

where X is the actual aggregate of weights x unit moves. The breakdown of this calculation lies in the invalid procedure used to figure unit moves. Mr. Smith says to find X by ". . . summing up all the numbers [meaning weights] which are the same unit distance away from the diagonal and multiplying this value times the unit distance from the diagonal." *This calculation is valid only if we assume that our plant is to be laid out in a straight line.*

Along these same lines, Mr. Smith says that when the headings are properly rearranged on the chart, the 100 per cent efficient situation will appear with all numbers located in squares adjacent to the diagonal. This also is dependent on the use of a straight-line layout.

A simple example will illustrate the weakness of his efficiency analysis.

Part No.	Movement in Weight-Distance Units Per Mo.	Sequence
I	100	A, B, C, D
II	200	A, C,
III	300	C, D, B

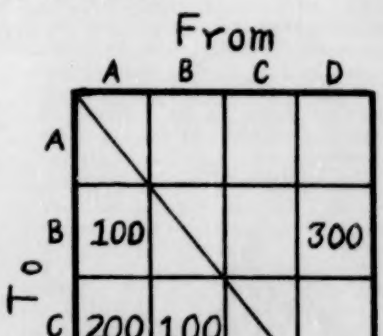
The theoretical 100 per cent efficiency movement value is

$(100 \times 3) + (200 \times 1) + (300 \times 2) = 1100$

Smith's efficiency formula would then be

$$E = \frac{1100 \times 100}{X}$$

Transferring the data to a chart, we get the following*



*Note that no special penalty is awarded to "backtracking" in this example.

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The Criteria of Engineering

By Everett Laitala,

Professor of Industrial Engineering, Case Institute of Technology

The need for establishing the measurable characteristics of engineering in terms of its objectives and the means to attain them can be appreciated more by the Industrial Engineer, perhaps, than by most of those in other branches of engineering. However, one must hasten to say that this problem of quantification of engineering is not peculiar to any branch of engineering, for all branches are identified by names which possess the common term engineering. The adjective in the name helps to establish the characteristics of a particular sub-division, or branch, of engineering. The reason for suggesting that the Industrial Engineer may be more conscious at this time of the matter of definition is that he functions in one of the newer areas of engineering and, thus, seeks clarification of purpose and identity in the engineering family. As such, the need for standardization of terms and practices is becoming imperative. The history of older branches of engineering is simply being repeated. The need for defining Industrial Engineering is important, but that can be accomplished only after the noun engineering itself has been defined. Once this is done, the adjectives, Industrial, Mechanical, Electrical, Civil, etc. can be defined with greater ease. While many of us have felt, at times, that the problem of definition of Industrial Engineering was unique among the various branches of engineering, a little investigation would reveal the same dilemma in all branches. Paul DeGarmo very effectively directed attention to this in the February 1953 issue of the *Journal of Industrial Engineering.*

That there is a real need for continuing a thorough study of the specific nature of engineering and the establishment of its measurable characteristics is manifested in a number of ways. The problem of trying to define Industrial Engineering has been mentioned as one example. The Engineers Council for Professional Development in its accreditation work must have sound yardsticks for use in differentiating between what is an engineering course and what is not. It certainly ought to know what the specific objectives of any engineering curriculum are. To this extent, it has developed some criteria for use by its inspection committees. Although excellent work has been done in formulating these criteria, much needs yet to be done.

Those of us who have participated on Engineering-College Policy and Curricula Committees are familiar with the amount of curricula development that goes on without a concrete set of standards. Everyone argues for the teaching of fundamentals and everyone is against teaching "cook book" engineering. It's time the record is changed to play a tune "Fundamentals for What?"

It has been the author's experience at three engineering schools that hardly a single last semester senior will dare attempt a definition of engineering. This would suggest that engineering is an end in itself and needs no definition. One seeks, too, the criteria of engineering when he observes the changes which are taking place in the colleges of engineering. Where engineers once led and taught, we have the growing trend of leadership and instruction which, by training and experience, is the fartherest removed from the end product of engineering—"the adaptation of science to human needs."

The need for a sound grasp of the basic nature of engineering is needed as much in industry as in an engineering college. The disproportionate use of engineering talent on tasks which could be performed by persons with non-engineering training is one example. Another is manifested in the confusion that exists in industrial organizations regarding grouping of functionally similar engineering activities. I have particular reference to those that are basic to "process design." In this connection we might observe, for example, the term Industrial Engineering. The use of it as a label for a department, which is an arbitrary grouping of work, rather than as representing a body of engineering fundamentals, is a "curse" which we in education will have to face pretty soon. Development of a broad professional society under that name suffers from the same "curse."

The writer is fully aware, too, of the difficulties that confront anyone who attempts definition and quantification of the term engineering. He has found, however, encouragement and guidance from the following two paragraphs under the heading "What is Engineering?" from the work of Professors Hoover and Fish.(1)*

"Terms are tools. An engineer's first concern is that his terms be sharp and adapted to their purpose. He knows that a problem well defined is half solved, that a flock of difficulties take wing at a close approach to exactness in the sense in which a term or symbol is used. Hence, an engineer looks for a clear and exact definition of his own profession.

"Some engineers not satisfied with any dictionary definition, have tried their wits at making their own from time to time, with the hope—so far in vain—of giving general satisfaction to their brothers in the profession. These definitions have been criticized as including much that is not engineering, as failing to include much that is engineering, or doing both. This is not to criticize the makers of these definitions; they deserve the thanks of the profession for their efforts. To write an entirely satisfactory definition may be impossible." (1, pg. 10)

In short, these two paragraphs tell us that it is essential that we have objective goals and that to define them is a difficult task. The writer feels, however, that the studies which have been made so far in the nature and characteristics of engineering have been primarily carried on by engineers whose basic characteristic is "product design" and that valuable contributions can be made by engineers whose basic characteristic is "process design."

Present State of Definitions and Criteria of Engineering

To provide some historical background for the "present state of definitions" it will be desirable to note the following:

"The Institute of Civil Engineers of Great Britain was organized over a century ago. At that time 'civil engineer' meant any engineer not formally engaged in military work. Thomas Tredgold, a successful practitioner and well-known writer on engineering topics, was asked to write a definition of the term; his statement was adopted (1828) and is today printed on all publications of the Institute. 'The art of directing the great sources of power in nature for the use and convenience of man'; nothing better

*Numbers in parentheses correspond to references so numbered at the end of this paper.

nas been written for the purpose. It is still a good definition for all branches of the profession." (2, pg. 129)

To the author's knowledge, one of the most extensive and thorough studies of the specific nature of engineering and the engineering method is to be found in the work of Professors Hoover and Fish, previously referred to. Their 485 page book is a summary of considerable research and analysis on the subject and should be on the "must" list of reading and study of every engineering educator and practitioner.

What appears to the author as the most objective short statement on the nature and characteristics of engineering is to be found in the "18th Annual Report of the Engineers Council for Professional Development" under the title "Differentiating Characteristics of an Engineering Curriculum." This statement is the work of the Education Committee in which is invested the responsibility for accreditation of engineering curricula. The following paragraph from the report of this committee directs attention to problems it faces in its accreditation work.

"Many engineering schools have catered to the popular demand for specialized training in a wide variety of engineering specialties. As a result, there exists today some confusion as to what really characterizes an engineer, or, indeed, a curriculum suitable for training for any of the branches of engineering. It appears timely, therefore, to examine this situation and to prepare, if possible, a compact statement of what characterizes engineering training. In fact, if accreditation is to be successful, curricula so accredited must contain such characteristics as may readily identify them as engineering curricula." (3, pg. 10)

Present Definitions

Before presenting them for analysis, it is necessary to establish some basic concepts and standards for their evaluation. In the first place, it is essential to recognize that a definition is a standard and that if it is to be a sound standard, certain fundamentals must be applied in its formulation. In other words, before we can establish a definition of engineering, or anything else, we must know what fundamental elements are essential in a standard, whatever its nature.

An excellent reference, and one of the few available on the subject, is *Industrial Standardization, Its Principles and Application* by John Gaillard. (4)

He makes the following observations: "A standard comprises three fundamental points, namely:

(1) A standard is a formulation. A standard is defined as a formulation because in its perfect form it is the result of putting ideas into a clear and definite form of statement or expression.

(2) It serves to define, designate or specify certain features of one or more objects enumerated in the definition.

The degree of exactness with which the requirements of a standard are formulated, therefore, determines its effectiveness as a guide leading toward agreement between different parties. Special importance is attached to this point as a standard usually is the result of compromise often reached after long and difficult negotiations. To leave doubt about the meaning of its specifications is to defeat, at least in part, the purpose for which the standard is set-up.

(3) It serves in this capacity during a certain period of time."

A standard is set-up in principle as a temporary constant level of requirements and is, therefore, meant to remain valid for some time.

Having established the standards for evaluation of the definitions of engineering, we shall now examine the definitions of Hoover and Fish and of E.C.P.D. The former say that "*Engineering is the profession and systematic application of science to the efficient utilization of natural resources to produce wealth.*" (1, pg. 10). This systematic statement characterizes the first characteristic of a standard, namely: "A standard is a formulation." The authors have not overlooked the second characteristic "to define, designate, or specify certain features of one or more objects enumerated in the definition." Chapter II of their book indicates that much thought was given to each item in their definition since each of them was defined separately. There is, however, the shortcoming in the above statement that the units for evaluation of "an engineered job" are not singled-out as the summary in Fig. 1 indicates. The author wishes to note, however, that Hoover and Fish did not overlook this, for a concluding statement at the end of the chapter referred to states "this chapter has been confined to some preliminary exploration of engineering as a whole." Also, their recognition of so-called "primary points of comparison" in engineering projects confirms this (1, Chapter 10). It is unfortunate that they did not include these objective measures in their general formulation. The definition as given above is arranged vertically in the left column of Figure 1 and excerpts from their clarifying statements are given in the right column.

Definition (Hoover & Fish)	Clarifying Statement
Engineering is the:	
1. Professional	"A calling has become a profession (1) when to practice it one must have acquired a fund of special, organized, theoretical learning and training in applying it."
and	(2) "When it recognizes that above each member's responsibilities to his client, his colleagues, and himself, is his responsibility to the public."
	(Engineering meets both tests of this criterion and is therefore a profession.)
2. Systematic	"The engineer applies to his professional problems a systematic way of thinking, which has come to be termed the engineering method."
3. Application of Science	"When a person is applying science—that is, bringing it to bear on a particular problem for practical ends—he is practicing a useful art. Engineering is not a science, but rather, an application of science. In other words, engineering is an art; it is the practice of skill and ingenuity in adapting knowledge to the uses of man."
to the	
4. Efficient Utilization	"The search for maximum efficiency in the application of science to industry is a problem of economy; for economy seeks the highest possible ratio of utility to cost in the long run—the most profitable employment of human effort and natural resources or of organized effort of any sort."
of	
5. Natural Resources	"From the engineering point of view natural resources may be classified as 'materials' and 'power.'"
to	
6. Produce Wealth	"Those things which serve a useful or desired purpose and cannot be acquired without sacrifice of labor, capital, or time."

Figure 1

The author wishes to remind the reader, again, that the excerpts in the summary or Figure I are just that and that a full reading of the source material is recommended.

We shall now analyze the E.C.P.D. definition in a similar manner. The definition follows along with a prefacing statement which is essential to the understanding of it.

"Essentially, the Committee (E.C.P.D. Education Comm.) determined upon *ability to design* as the significant and distinctive element in the background of the engineer. It was proposed, therefore, that training for this ability be recognized as the distinguishing characteristic of engineering education, and that for this purpose, the term 'design' be treated in a broad sense as follows: *"An engineer is characterized by his ability to apply creatively scientific principles to design or develop* structures, machines, apparatus or manufacturing processes, or works utilizing them singly or jointly or in combination; *or to construct or operate* the same with full cognizance of their design, and of the limitations of behavior imposed by such design; *or to forecast their behavior* under specific operating conditions; *all as respects an intended function, economics of operation and safety to life and property."* (3, pg. 10, 11)

This definition is rearranged in Figure 2 to permit closer analysis.

When we compare the two formulations of engineering discussed above, we observe that that of Hoover and Fish expresses the goals of engineering in generalized terms and that the definition of E.C.P.D. describes largely the means by which these goals are attained. The latter observation is supported by a comment in the E.C.P.D. report, "No attempt has been made to describe all the functions that engineers may perform in the course of the practice of engineering. Instead, the differentiating characteristics have been sought by which the engineer's work may be recognized from the work of others."

These definitions must be looked upon as implementing each other. Every item in the E.C.P.D. definition can be related to a specific item in the Hoover and Fish definition. The real contribution which the former makes is that it does begin to "define, designate, or specify." To say that that of Hoover and Fish does not is really not correct, for if their definition is studied in relation to Chapter III of their book, we would note a rather direct parallel between the two.

Let us assume that the above definitions and combinations of them are the best standards we have as a basis of determining what engineering is and what it is not. What are their shortcomings? Attention to these can be directed best, perhaps, by further questions.

(1) If we say "the whole creative process extending from the initial conceptual thought to the subsequently refined plan is here meant as design," and that, "It may be achieved through mathematical or developmental procedures, but it utilizes scientific principles," how do we differentiate the mathematician, the physicist, or chemist from the engineer? Where do we draw the line?

(2) What is the specific goal of engineering, anyway?

(3) If "the ability to design" is the basic characteristic of the engineer, what specifically are the plans which result from the design process?

(4) What are the measurable characteristics of "intended function," "economics of operation," and "safety to life and property."

Other questions could be asked, but those raised are adequate to emphasize the need for further developmental work. As previously stated, it is the purpose of this paper to attempt a further quantification of the definition.

Definition (E.C.P.D.)	Clarifying Statement
An engineer is characterized by his ability to:	
1. Apply creatively 2. Scientific principles	"It is in part a characteristic of the engineer that he applies scientific principles in design, construction, and operation. This differentiates him from the artisan who constructs or operates without scientific knowledge."
to	
3. *Design or develop* structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or jointly or in combination.	"It is recognized that the words 'design' and 'develop' mean different things to different people. They are not here used in the narrow sense usually attached to them in engineering offices, where some are 'designing,' some 'detailing,' others 'developing,' and so on. The whole creative process, extending from the initial conceptual thought to the subsequently refined plan, is here meant as design. It may be achieved by mathematical or developmental procedures, but it utilizes scientific principles."
or to	
4. *Construct or operate* the same with full cognizance of their design and of the limitations imposed by such design	"The engineer, furthermore, constructs and operates within the framework of limitations inherent in design; and to do such constructing and operating he must be fully conversant with the design and its limitations."
or to	
5. *Forecast* their behavior under specific operating conditions	No further clarification given.
all	
6. *As respects* an intended function, economics of operation, and safety to life and property.	"Such design is not aimed primarily at aesthetic or functional objectives alone, but in addition, characteristically includes objectives involving economics and safety. The economic objective in part distinguishes the work of the engineer from that of the scientist or the artist."

Figure 2

Basic Assumptions

The discussions which follow are predicated upon the following assumptions:

(1) *That engineering is concerned with making the properties of materials and forces in nature useful to mankind.* None of the many definitions available contest this overall goal.

(2) *There is a difference in the number of criteria to be met in a society where engineering is tested by the dollar votes of a consumer and that in which it may be protected by a totalitarian system, a monopoly, a cartel, or subsidized activity, as for war.* Proof for this will evolve in discussions which follow.

(3) *If the engineer is to meet the obligation of making the properties of materials and the forces of nature useful to mankind, he is forced to meet this obligation best in a setting where economic activities are conducted on a competitive basis.*

Consumer Criteria

Is our definition of engineering satisfied when an engineer makes something *available* to mankind, such as electricity, an automobile, a new material, an airplane, an electronically controlled milling machine? The answer is no, for mankind has on many occasions in a free-choice economy decided that many items and services which were available could not be "useful" to him. The history of business failures in the U.S. is supporting proof to this statement. We should observe, of course, that a business failure may not be traceable to poor engineering only, but that other functions of the enterprise may not have carried out their tasks satisfactorily. It could be said that the engineering in a particular case might be of a high order but that poor sales policies and practices, for example, may be the cause for failure. All this adds up to the fact that what is made available to mankind is the sum total of the activities of many persons and disciplines and not engineering only. What is of real interest to us is the determination of what criteria mankind uses in deciding whether or not a product or service can be useful to him. These criteria should be the standards for analyzing and evaluating the nature and quality of engineering and any other activities carried on in business enterprise.

What are these criteria? What is it that mankind desires in the things and services that it wants. The criteria seem to be the following. They will be identified qualitatively first and in later discussion the quantitative features will be identified and illustrated.

1. *Function.* The product or structure must perform the function for which it is intended. A pen must write, a can opener must open a can, a bridge must permit travel over water or a gully, a boat must permit travel on water, etc. In other words, what is made available to mankind must, in the first place, serve some need if it is to be wanted. There are, of course, generally alternative ways in which the functional requirements of a need might be met. The crossing of a river might be effected by means of a pontoon bridge, or a rigid structure of wood, steel, concrete, or aluminum, or by ferry, or by combinations of them. These alternatives suggest, then, a second basic criterion, namely; quality, a discussion of which follows.

2. *Quality.* If we assume that a product or structure will perform the function for which it is intended, then our next desire is that the product or structure meet certain quality standards. The characteristics of quality are essentially threefold, as suggested by the following questions:

(a) How well does each alternative perform the function for which it is intended?

(b) How well will each alternative stand-up in service?

(c) How efficiently will each alternative function?

If we consider a vacuum cleaner as an example, the above questions might assume the following form:

(a) How well does each alternative remove dirt from a rug.

(b) What maintenance will be necessary and what is likely to be the life of the alternative?

(c) How much electricity will each require to do the same job?

In short, a product or structure to be wanted by mankind must meet his quality standards to an acceptable level.

3. *Cost.* While a product or structure may be sound from the standpoint of *function* and *quality*, it may not be useful to us because we cannot gain possession of it. Ownership is necessary in most cases before a product or structure can satisfy our wants properly. In other cases, we get to use them by stealing, borrowing, or renting them. Money is the means by which we gain right to use or own most of the want satisfying things available to us. Cost to us is, therefore, a third measurable criterion to be met in meeting the needs of mankind.

4. *Date.* While a product or structure may meet the above three criteria to the satisfaction of mankind, it may still not be useful to him because it will not be available when he wants it. A product scheduled to be available three months from now cannot be useful to a person who needs it next week. Mankind's needs are gauged to time. It wants most of its needs satisfied "right now" or the immediate future. Date when wanted, therefore, becomes a fourth measurable characteristic in the satisfaction of human wants.

5. *Other.* Criteria numbers 1, 2, 3, and 4 must be considered in every engineering project. However, there are other factors which can be placed in the category of "special." They are factors which have a definite bearing on the satisfaction of mankind's needs and may impose limitations on engineering. They are considered in the "special" category because these factors cannot be identified except in terms of a specific problem. Then too, at any one time, the factors may be of major consideration, and on the other hand, have no bearing at all. Eye appeal is of paramount importance in all items which may be in open view, but a gear to be assembled in a closed gear box need not be appraised in terms of this factor. Other factors in this special category might be service available, convenience in use, keeping-up with the Joneses, etc. In discussions to follow criterion # 5 will be largely overlooked. This will be done not because criterion # 5 is considered less important than the others in the decision which a buyer makes, but because, as indicated above, the factors involved cannot be identified except in terms of specific problems.

Summary

As indicated above, the criteria for evaluating the success or failure of a business enterprise in a free choice economy must be made in terms of what we will call the consumer criteria. Mankind by its willingness or unwillingness to buy a product or service determines the success or failure of an enterprise.

Assuming that a company has sound sales policies and practices, the next consideration is one of providing a product which will meet to the best advantage the consumer's needs. He wants something that will do the job for which it is intended (function); something that will stand up well in service and operate efficiently (quality); something that he can afford or is willing to spend money for (cost); something he can get when he wants it (date); and that it meets his "other" desires.

Measurable Characteristics of Engineering

Since in a free choice economy the consumer is the final inspector and judge of engineering, as well as of all other activities singly or jointly, the point of origin of our study must be the consumer. It is from him that we get the original specifications, and also we must look to him as the terminal point of a cycle of events since he will inspect the product in terms of his own specifications before making a decision to accept or reject. We shall now explain the consumer-to-consumer cycle of events by means of a chart, Figure 3, as a basis for clarification of the engineering process. It is well to emphasize that this chart recognizes only those elements of the cycle in which engineering is likely to be an essential ingredient.

CONSUMER-TO-CONSUMER CYCLE CHART

In order to appreciate better that which follows it would be well for the reader to study Figure 3 for a moment to grasp its general construction. It will be noted that it consists of three sections viewed vertically. The upper section describes in a qualitative way the general steps observed in the production and sale of goods. The various steps are identified by number. The center section establishes these steps in more quantitative terms. The purpose of the discussion which will follow shortly is to establish their measurable characteristics. The lower section of the figure identifies the fundamental phases of the cycle. These latter headings will be used in the presentation of the explanation of the chart.

Before presenting this explanation, it is important to observe certain cautions, namely:

1. The chart is based on functional divisions of work and is not to be interpreted in terms of any departmental grouping of work, as in industry. How the functions are carried out is not a consideration here. Students of organization, however, will recognize the chart as

CONSUMER-TO-CONSUMER CYCLE CHART

1	2	3	4	5	6	7	8	9	10
Consumer	Company	Company	Company	Company	Company	Company	Consumer	Consumer	Consumer
What he seeks in product	Must determine the consumer desires relative to each; where market exists; how many are wanted; through:	Attempts to meet consumer desires to best advantage by recognition of need for certain functional areas of planning.	Name of plan developed	Makes product in accordance with plans to best of its ability	Must evaluate work for conformance with plans as a basis for control	Must bring product to attention of potential consumer through:	Evaluates product for:	Makes a decision the result of which has a bearing on	After purchase of a product
Function Quality Cost On Time Other	Market Research	Product Design Process Design Schedule Design	Drawing Routing Schedule	Construction, Production, Operation.	Quality Cost Completion Date	Advertising and Sales Promotion	Function Quality Cost On Time Other	Degree of Success or the Failure of A Company	Operates or Uses Product
General Specifications Phase		Design Phase		Execution Phase		Selling Phase		Decision Phase	Maintenance Phase

Figure 3.

an aid to the study of so-called "basic functions" and as a foundation for "departmental" separation of activities.

2. Terminology should be looked upon as symbolizing or identifying activity. The intent of this paper is not to propose standard terms even though that would be a desirable objective. The important thing is to know the activity which the term is intended to identify. Having done this, the reader can then introduce his own labels.

With the above suggestions in mind, the elements of the chart will now be explained.

General Specifications Phase

Column 1. Previous discussions have brought out that there are some common and definable utilities which consumers seek in the products and services that they buy. These criteria are the points of origin and are therefore listed in the first column.

Column 2. Knowing the general nature of consumer wants, Column # 1, the next step is to determine specific characteristics of each. As indicated on the chart, this is accomplished through market research. This phase of the engineering process seems to be taken for granted, or is not recognized, as an essential step in the process. It is important to note here that it is the data collected through market research that "states the problem" or establishes the general specifications for the "design" activity described in Column # 3. If these general specifications are wrong, the results of the design activity are going to be wrong. There are many case histories to support this contention. Bridges, machines, and processes have failed to meet the demands placed upon them because "certain factors" were overlooked in the analysis of the problem itself. This phase is, therefore, no less engineering than the others which follow. "Whether the manufacturer's project was initiated as the result of some new invention, or as a laboratory or engineering development, or was originated through his learning of an urgent consumer need, his ideas, plans, and decisions must conform to many controlling factors." (5, pg. 29). An explanation of how these "controlling factors" are ascertained is not an objective of this paper. Suffice it to say that they might be obtained through a marketing research department in the case of mass produced products; through a purchasing agent where specifications are definitely established by drawings; or through the sales engineer, who ascertains the specific requirements to be met and those conditions which will impose limitations upon the design.

The result of the "General Specifications Phase" of engineering is, therefore, a *statement of the problem.*

Design Phase

Columns # 3 and # 4. Next we recognize that if a company is to meet to the best advantage the consumer's needs, it will have to plan how this can be accomplished. This planning must satisfy the general product specifications uncovered through market research and manifest itself in terms of the measurable characteristics of Column # 1; namely, function, quality, cost, and date, and limitations placed upon them by factors coming under the heading of "Other." Three basic areas of planning are needed to accomplish this; namely, product design, process design, and schedule design. The resulting plans are a drawing, a routing, and a schedule, respectively.

We are not concerned here with the details of how these plans are generated or what "departments" of an organization may contribute to them and how. Rather, we have as a specific objective the determination of the functional areas of engineering planning and the specific and measurable characteristics of each. Each area of planning will now be discussed.

Product Design

The product design area of planning is concerned with satisfaction of the *functional* and *quality* characteristics of consumer wants. Its results are found on the drawing, for example Figure 4. If we remove the dimensions and ma-

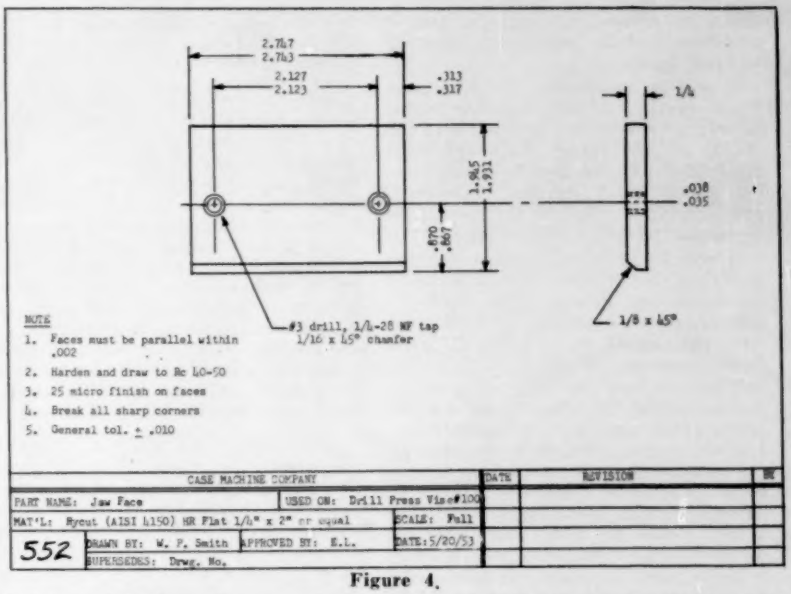


Figure 4.

terial specifications, there remains the "function" characteristic of design. When we add the dimensional and material specifications, we recognize the "quality" characteristic. It does not matter whether the product design area is Civil, Mechanical, Electrical, Aeronautical, etc., the drawing possesses these same characteristics.

That these characteristics are objective and measurable is attested to by our every day production of products and structures by persons who had no part in the preparation of the plan itself.

It is essential, at this point, to explain an important concept, since it pertains to the interdependent nature of the three design areas. The concept may be stated thusly: *each engineering plan must represent the optimum balance of the consumer criteria.* This statement says, in effect, that the plans resulting from the design phase of engineering are mutually interdependent. This means that the *product design* can, and does, dictate essential characteristics of the process design and schedule design; that *process design* can, and does, dictate essential characteristics of the product design and schedule design; and that *schedule design* can, and does, dictate essential characteristics of product design and process design. As each of the three planning areas is discussed, the reader should keep the above statements in mind.

In the way of summary, it can be said that the product design area of engineering derives its purpose from the measurable characteristics "function" and "quality."

Process Design

The process design area of engineering planning is concerned with the *cost* characteristic of consumer wants. Meeting this consumer specification cannot be left up to chance anymore than can the "function" and "quality" specifications. We are concerned here then with the means by which the product design can be effected. It involves analysis of the product design in terms of what productive operations are necessary and the determination of how they will be carried out; what machines, tools, and facilities are necessary; and what standards of output shall govern the performance; etc. This planning area can best be defined by the resulting plan in the field of manufacturing, the *routing.* See Figure 5. It is unfortunate that we do not have, as yet, a universally accepted term to identify this plan. However, it is not the name of the plan that we are concerned with here, but rather the plan itself. We have stated that its basic function is to aid in meeting to the best advantage the "cost" specification of the consumer. While the planning process and the resulting plan may vary in detail in various areas of engineering, such as Civil, Chemical, Mining, Ceramic, and Industrial, the important thing to observe, at this point, is that the *process design* function is performed.

In the way of summary, it can then be said that the process design area of engineering derives its purpose from the measurable characteristic, *cost.*

Schedule Design

The *schedule design* area of engineering planning is concerned with the *date* specifications of the consumer. As we have previously stated, neither product or process design can be established without due consideration of this specification. Schedule design conditions product and process designs in the same way as they condition it. It is, therefore, no less important an engineering area of design than the other two. It is, however, the least understood. It is a common feeling among engineers who have not had training in this area, that schedule design is basically a clerical matter. However, if one visualizes the industrial plant or construction plant, for example, as a huge machine, the problem of regulating flow of materials within this system becomes more than a paper processing matter. It can vary in nature from a highly integrated series of operations to a series of highly intermittent operations. Just as a draftsman may be capable of handling the product design area if present designs are going to be acceptable in the future, so, too, can a non-engineer continue to handle schedule design if the "status quo" is going to be acceptable.

On the other hand, if we study the relationship of schedule design to product design and to process design, we

ROUTING SHEET

Part Name: Jaw Face
Material Specifications:
1. Kind: Rycut (AISI 4150)
Part No.: 552
Model: Drill Press Vise
2. Size: HR Flat 1/4 x 2
Date Effective: 5/27/53
No. Per Model: 2
3. Amt. Req'd. per Pc.: 1/4 x 2 x 2
Replaces Issue of
Lot Size: Min. ___ Max. 100
4. Other
Sheet No. 1 of 1
Flt. Layout Drwg. No. 1231
5. Scrap Factor: 5%
By: WFS Chk: MS App'd: WAL

Oper. No.	Dept.	Description of Operation	Machine	Tools	Operator Spec.	Standard Time (Hrs) Set-up	Per Pc.
10	1	Cut to length. Remove burrs.	S-1		1234	0.1	.017
20	1	Surface grind one side to clean-up	G-2		2930	0.5	.050
30	1	Surface grind other side to clean-up	G-2		2930	0.5	.035
40	2	Mill bottom (5 pcs per load)	M-1	552-40	2502	0.5	.033
50	2	Mill top to 1.937 (5 pcs per load)	M-1	552-40	2502	0.5	.033
60	2	Mill 1/8" x 45° chamfer. (2 pcs per load)	M-2, 1	552-60	2502	0.8	.020
70	2	Mill one end (1 pc per load)	M-2, 1	552-70	2502	0.5	.040
80	2	Mill other end. Hold 2.745 (5 pcs. per load)	M-2, 1	552-80	2502	0.5	.033
* 90	4	Starting drill and flat bottom #) drill (2) holes	BP-2	552-90	2703	0.5	.067
100	4	"2 starting tap and finish tap (2) 1/4-28 holes	BP-3, 4		2703	0.5	.067
110	1	Remove all burrs		File	3810	0.2	.017
120	6	Harden and Draw RC 40-50			4511	4.0	.040
130	6	Pentrate			4511		
140	6	Inspect			1100		
150	6	Move to Stock Room			1301		

Figure 5.

shall discover the important engineering relationships involved.

Schedule design manifests itself in a schedule as shown in Figure 6.

In the way of summary it can be said that the *schedule design* area of engineering derives its purpose from the measurable characteristic, *date*.

Summary for Columns # 3 and # 4

The *design phase* of engineering is the important one to study for it manifests most objectively what E.C.P.D. has termed the basic or differentiating characteristic, of engineering; namely, ability to design.

If engineering is to be understood, the basic characteristics of the three areas of design must be understood. A proper appreciation of them can be gained only from an objective study of the plans which manifest them.

There are three basic engineering plans:

1. Drawing
2. Routing
3. Schedule

They are not ends in themselves. Rather, they are means for communicating information.

As the above named plans indicate, an engineering problem is one upon which is always imposed simultaneously the specifications of function, quality, cost, and date. As indicated previously, there are, of course, "Other" factors which may at times modify them.

Execution Phase

Columns # 5 and # 6. These columns identify what shall be called the *Execution Phase* of engineering. It consists of the transformation of the shape and condition of materials in accordance with the drawing, routing, and schedule and the evaluation of actual performance against the standards on these plans.

Because of the increasing complexity of products and processes and their control, there is an increasing need for the persons in the Execution Phase, who direct the efforts of others, to have a sound grasp of the "limitations imposed" by their design.

It will be noted that the Execution Phase consists of two separate parts; namely, production and evaluation of the results of production. Each are regulated directly by the three basic engineering plans. Each requires engineering direction if the intent of the plans is to be carried out to the best advantage.

It will be noted in Column # 5 that the terms Construction, Production, and Operation are given. They are considered here as carrying the same basic meaning. What is actually produced is the basis for the use of the different terms.

Construction is a term used in connection with making of dams, buildings, highways, etc. *Production* is used in connection with manufacturing industries. The term *operation* is used in connection with plants generating electricity, water pumping plants, sewage disposal plants, etc.

For a more complete clarification of these terms, it is suggested that the reader refer to Hoover and Fish. (1, pgs. 26-28)

In the way of summary, let us observe again that the end objective of engineering is not a technical paper or a set of plans, but rather the making of the properties of materials and the forces of nature useful to mankind. The Execution Phase of the engineering process is an essential step toward making that a reality.

Selling Phase

Columns # 7 and # 8. The next step in the engineering process is referred to as the selling phase. The importance of this phase is summarized well in the following quotation:

"Objects or services produced are valueless unless exploited, properly applied, and accepted by those who can use them. In this respect, sales engineering, through avenues of distribution serves as the essential link between those that produce and those that use. (6, Page 7)

"Goods which are widely used and highly standardized and those which most people know about constitute merchandise and are distributed and sold by merchandising methods. On the other hand, goods which must be fabricated, tailored, or adapted to meet a particular requirement or those which find their usefulness only in relation to their ability to meet an exact set of conditions existing in industry, are sold by means of technical skill which *interprets* and *applies* the goods for the individual buyer. In the distribution and sale of such goods, engineering skill forms a vital and necessary part." (6, pg. 5, 6)

In this phase, the consumer evaluates the product to determine the functional characteristics; how well it will stand up in service, and how efficiently it will operate; he ascertains the price; he inquires of the date when he might possess it; and he considers "the other" factors—appearance, service available, etc. He appraises the product of one competitor against that of the others. He is, therefore, the final inspector of the product and of engineering.

In the way of summary, we should observe that what might have been a "well engineered" product up to this point might be converted into an "engineering flop" by lack of appreciation of the "limitations imposed" by the design. It is, therefore, not an accident that more and more engineers are required for what we shall call the *selling phase* of engineering.

Decision Phase

The difficulty and complexity of deciding which one of a number of alternatives should be selected depends upon whether the product to be selected is one which is "widely used and highly standardized" or one which must be "adapted to meet a particular requirement." It is in connection with the latter category, generally, that engineering becomes an essential ingredient. It is, therefore, proper to recognize that with the increasing complexity of materials and products and their specifications that the purchasing function increasingly becomes an engineering function. For sound decisions there must be a full awareness of the "limitations imposed" by the design.

The consumer decides. He casts a vote for the product of one company and a vote against the product of each of the competitors. The success or failure of a company depends upon its ability to capture an adequate number of these votes. This observation should remind us again that engineering is not an end in itself, but rather an aid in meeting to the best advantage those needs which mankind possesses.

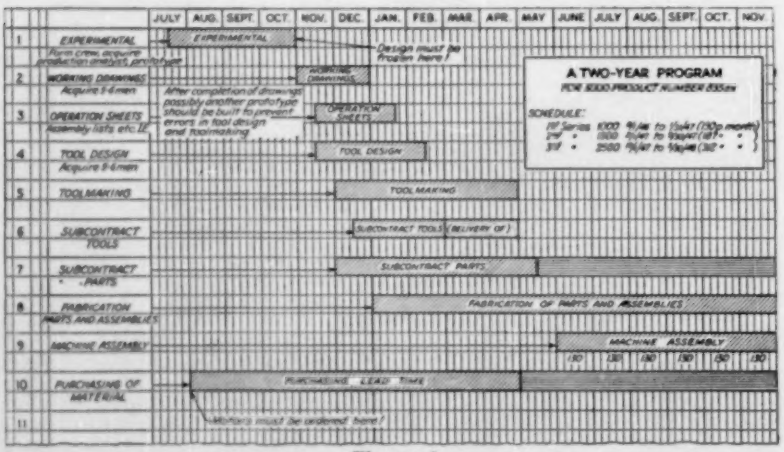


Figure 6.

(Reproduced with Permission From Plant Production Control, C. A. Koepke John Wiley and Sons, Inc., New York, Second Edition, pg. 331)

Maintenance Phase

Column # 10. It is not enough for a company to design, build, and sell a product. It has to often provide additional services and follow up to assure consumer satisfaction. Contracts often call for *installation* and *maintenance* service. The former we recognize as a productive type activity which we described under the heading Execution Phase. The latter activity, however, has not been discussed as a phase of engineering.

Because of highly technical nature of modern equipment and facilities and the demands placed upon them, direction of maintenance activity is becoming more and more of the kind which only an engineer can direct. While there is much work of the actual *design phase* involved, the greater portion of the activity is characterized by decisions which require full knowledge of the "limitations imposed" by a particular design. The growth in the use of automatic controls and devices in more and more complex machinery will require greater and greater attention to the *Maintenance Phase* of the engineering process.

This concludes the cycle of events which began with the consumer and ends with the consumer. It is, therefore, a closed loop system. Engineering is not a single step, but rather, several steps. It is a process.

Some Suggestions for Improvement of the Definition

At best, the most any individual person can do as regards the establishment of a standard is to contribute data which may be helpful to an organized body of persons whose function it is to evolve an "exact fixation of the different items of the standard by definition, designation, or specification." (4, pg. 35)

It is a sad commentary on the engineering profession that it recognizes the need for continuing standardization committees covering bolts, nuts, packaging, materials, etc., but not one assigned a specific responsibility to "apply creatively scientific principles" to the design of a sound standard for engineering itself. The work of the E.C.P.D. Education Committee in this direction has been excellent. Its function, however, is not to develop a standard, but rather to apply it to its accrediting procedures and standards.

Not having an acceptable standard available, it has had to evolve its own. The engineering profession should recognize the need for further work through establishment of a committee assigned specifically to this matter.

The objective of this paper was not, therefore, one of proposing a new definition, but rather to "analyze some basic concepts of engineering and to attempt to reduce its characteristics to a more quantitative foundation." It is hoped that its contributions will be helpful in quantification of the definition of engineering.

In order that the author shall not be accused of "leaving the hammer in the air at the sound of the dinner bell," it is desirable to present a summary of the contributions which he feels the paper makes to the question at hand.

Summary

1. It recognizes the difference between making something "available" to mankind and "useful" to mankind. The latter is associated with a competitive system which gives the engineer his most critical test through the dollar votes of the consumer. The former is associated with a protective clothing supplied by a totalitarian system, a monopoly, cartel, or government subsidized activity. Unfortunately, the effects of "training" under one form of this protective coating are beginning to manifest themselves too strongly in attitudes in industry and on college campuses in this country. It is of interest, for example, to ponder the long-run effects of following facts. "The part which the defense program played in the expansion of research staffs is shown still more clearly by figures on the change in employment on government and non-government research work. The number of research engineers and scientists doing government-financed research rose by 52% between January 1951 and January 1952 in all industries taken together, whereas the number on non-government research work increased by only 5%." (7, pg. 13)

2. It emphasizes that in a competitive system, it is the consumer (individual, industrial, etc.) that dictates the general specifications or goals of engineering.

3. It recognizes that the basic areas of economic activity, in which the ability to design structures, machines, or processes is an essential characteristic, can be identified objectively by an analysis of the consumer-to-consumer cycle, Figure 3. The mere fact that these areas are not fully exploited, or in some cases hardly touched, in terms of this ability to design does not change this conclusion. This ability to design can manifest itself in six basic ways; namely,

a. General specifications
b. Design
c. Execution
d. Selling
e. Decision
f. Maintenance

4. It establishes that the criteria of any engineering activity are identifiable and measurable in quantitative terms; namely, function, quality, cost, date, other.

5. That the criteria are identifiable and measurable in quantitative terms is proven by actual performance today in which the various phases of engineering, as defined in this paper, are carried on by separate groups of people functioning in different "departments" and in many cases, hundreds and thousands of miles apart. For example, on one side of the globe we have an engineer who determines the general specification of a need which has arisen. He is able to communicate it in such measurable terms that someone else working independently can evolve a specific design incorporating properties (function, quality, cost, date, other) in such a way that someone else working independently can effect this design into a physical object which will meet the need for which the object was designed and made.

6. It shows that there are only three basic areas of engineering planning, regardless of field, and that they derive their purpose and measurable characteristics from desires of the consumer. These areas are product design, process design, and schedule design. The resulting plans for each, along with identifying characteristics, are shown in Figure 7.

7. The 3 areas of design are mutually interdependent. Each imposes limitations upon the others. What appears on the drawing, or routing or schedule, respectively, is not the result of the effort of one design group only, but rather the result of the contribution of all three. Each resulting plan is the "best compromise" for meeting to the best advantage

(Continued on Page 29)

Area of Design	Resulting Plan	Consumer Specs. Covered	Examples of Measurable Characteristics
1. Product	Drawing	Function & Quality	Form, Gal's. Per Min., 1.000±.002
2. Process	Routing	Cost	$ Per Lb.; 2.00 min./pc.
3. Schedule	Schedule	Date	Jan. 15; 10:00 a.m.; 6 wks.

Figure 7.

THE ASSEMBLY LINE BALANCING PROBLEM

By M. E. Salveson[1]

Major Appliance Division, General Electric Company, Louisville, Kentucky

An increasing number of industrial problems in programming and scheduling now are being solved by analytic procedures. Yet, the almost universal problem of balancing an assembly line does not appear heretofore to have been so treated, even though the first known assembly line was established as early as the War of the Revolution by Eli Whitney for the manufacture of muskets. Efficient procedures for handling this problem are highly desirable. A very large percentage of all commodities, both civilian and military, are manufactured by assembly line methods, so that any improvement in these procedures would have a very broad area of impact, in both peace-time and war-time production.

This paper reports our initial results in attempting to develop such a procedure. While refinements are expected with increasing experience and further research, it is believed the practical usefulness of the analytical, engineering approach to this manufacturing problem is demonstrated by present results. Indeed, substantial improvements in productivity have been achieved in each of several cases in which it was used. In addition, the present procedure lends itself to machine computation, such that it likely will be possible to compute optimum balances for assembly lines for many different levels of output in advance and thereby permit reduction by two or three weeks the lead time required to change the rate of production when required by changes in sales.

The Assembly Line Balancing problem is characterized by several challenging properties, including discreteness and technological precedence relations among the elements. The mathematical problem as usually translated from practical context is to minimize a function measuring idle time which is defined over a permutation group of work elements, the members of which are subject to technologically determined precedence relations on their possible temporal sequences. A solution must satisfy a system of restricting inequalities on the sums of operation-time values for combinations of the work elements.

Somewhat similar problems have been considered by other writers; for the purpose of orienting this paper relative to theirs, we mention several. Johnson (6)[2] considered a two and a three stage "book binding" problem which appears to be similar. However, it is concerned with the cases of two and of three sequential operations on a series of lots of different commodities, each of which is different, but the operations are on the same machine for these different commodities; also it allows non-trivial amounts of storage of the in-process items, a factor not present here. Barankin (1), DeCarlo (5), Rothman (8), and Salveson (10) have considered the problems of discrete fabrication scheduling. That problem allows storage, alternative routings, and different process sequences as between different commodities. The problem here does not allow these, hence it is both practically and mathematically less general.

The "Assignment Problem" treated by von Neuman (11) and by Votaw and Orden (12) is most similar of all to the assembly line balancing problem. However, it is somewhat less general than the line balancing problem in that the Assignment Problem is concerned only with the assignment of one job to each person rather than a set of ordered and timed jobs to each person. Muther (7) provides several useful suggestions. His is the most systematic of the many intuitive analyses of this problem. However, he does not seek either mathematical representation or analytic solution.

Assumptions

The objective here is to develop a procedure for "balancing" an assembly line for any commodity, although the particular assembly line studied was for one of the major appliances of the author's company. Without alteration, the procedure subsequently has been used also in balancing assembly lines for other appliances. In order to restrict the scope of the problem, we assume as given the demand which is forecast by the marketing department and the corresponding production rate necessary to meet that demand, i.e., we assume demand is certainly known. We do not consider any statistical problems of forecasting or of weighting which would arise from over or under production in relation to the demand that actually might be realized. We assume that the basic technologies of commodity design and production method are determined and unalterable. We assume determinism in the production rate function (work standard) by using Company experiental data on allowances for normal stochastic perturbations in production.[3]

Description of Problem

Within these assumptions, the problem in balancing is as follows. The commodity to be assembled is comprised of many different components, each of which typically is a fabricated "piece part" or sub-assembly of piece parts. The fabrication department endeavors to maintain a supply of these components on hand sufficient at all times to meet the requirements of the assembly department. (The problem of supplying these components is the "fabrication scheduling problem" mentioned earlier.)

Because of technical considerations, it is necessary and/or desirable to assemble the component parts of which the commodity is comprised in some specified sequence or set of sequences; that is, there is an ordering upon the sequence in time in which the parts may be assembled. For example, in dressing each morning (i.e. in assembling one's clothing onto oneself) it is typical to put on one's socks before one's shoes, rather than vice versa; different functional assemblies would be obtained from each alternative. In assembling an appliance (or virtually any commodity) it is necessary to observe corresponding precedence relations among its component parts. For example, one must insert a holding screw before installing and

[1]This paper was inspired by an original suggestion of the problem by W. B. Helgeson. Sincere appreciation is due him for his interest and cooperation in developing and testing the concepts reported here. Appreciation is also expressed to W. W. Smith for his valuable assistance and cooperation. It was originally presented at the 1954 Annual meeting, A.S.M.E.

[2]Numbers in parenthesis ( ) indicate the number of the reference listed at end of paper.

[3]This assumption caused some difficulty in relation to the inadequacy and incompleteness of most present predetermined motion-time data systems for use in more refined programming and scheduling procedures.

tightening its nut; one must position the housing before attaching other parts to it, etc. On the other hand, some of the assembly operations are not so restricted by a precedence relationship. For example, a name plate can be attached at any time between the time at which the housing is assembled and the time at which the otherwise finished appliance is crated. Some parts can be installed with increasing difficulty over a range of stations along the assembly line as other parts are assembled around their locations and access to them becomes increasingly difficult. Some parts can be installed in "logical" economic connected sequences; for example, a group of six holding bolts can have their nuts tightened by one operator or by up to six, (or even more) operators. But, each time an operator assembles one or more bolts, he must "pick up" the tightening tools. Obviously, there is an economy if the same operator tightens all bolts and is required to "pick up" the tool only once. Finally, some parts require that the operator stand in a specified position relative to the commodity; if he must walk to other positions for other tasks, there must be an allowance for walk time.

For technical completeness, we describe the familiar concept of assembly line "cycle time." If the quantity of production for a particular period is specified, and if the rate of production is to be uniform over that period, then the unit rate of production is determined simply as the desired quantity of production divided by the number of units of (effective) production time existing in that period. So long as that unit rate of production is met, of course, the forecasted sales requirements will be satisfied. However, the "method" of assembling the comodity in order to meet the demanded rate of production may vary considerably. On the one hand, it is possible that one or a small group of operators may assemble all component parts of one unit of the commodity at a time while working in a fixed location. Sufficient numbers of these groups of operators then are employed and they work independently of each other to attain the desired combined or total rate of output. On the other hand, and at the extreme, it is possible to use the familiar technique whereby all units of a commodity are assembled by moving them successively and uniformly along a conveyor in front of a series of operators, each of whom assembles one or a small number of parts onto each unit of the commodity as it passes in front of him. (This is the familiar "mass production" method for which American industry is celebrated.) The amount of time elapsing between successive units as they move along the conveyor is termed the "cycle time" for the assembly line.

This sequential assembly method has, of course, many important advantages. It often permits more specialization of task and more efficient use of personnel and facilities, it minimizes handling requirements, etc. However, it imposes an interesting requirement—and which is the basis of the balance problem discussed here. Each assembly operator must be assigned a number and combination of jobs (parts to assemble) such that the sum of the times required to carry out his assigned tasks is equal to or less than the cycle time. If his assigned work requires an amount of time greater than cycle time, he will not be able, obviously, to perform all of his tasks or will be unable to maintain his position on the line and will have to fall behind. Of course, if the work time assigned to any operator is less than the cycle time, he will be idle part of the cycle. This, of course, is an individual, an enterprise and a social loss arising from reduction in individual and group productivity. Indeed, we seek to minimize this loss.[4]

If any operator must move parallel to the assembly line while performing his task, it is necessary to allow "return to station" time in order to return to the original position so he may begin his work on each successive unit at that same position. Of course, the sequence in which the tasks are carried out at each station and the assignment of tasks to stations must be consistent with the precedence relations.

Each collection of elemental assembly tasks is termed an "assembly station." In our case, one operator is assigned to each station (although in some instances there may be more, we will not consider that case here).

Certain other technological relations result in the addition of some task performance times being non-commutative. For example, if operations a and b are performed on the top of an appliance and c is perfomed on the bottom, and if t(a), t(b), and t(c) are the times required to carry out these operations, then:

$$t(a)+t(b)+t(c)=t(a)+t(c)+t(b)$$

This is due, of course, to the different amounts of time required for the operator to move between the two locations under each assembly sequence. In the cases studied thus far, any combination of tasks carried out at different locations has been arbitrarily excluded as an admissible solution.[5]

If the basic tasks characteristic of assembly operations were continuously divisible, the problem of line balance would be trivial. Hence, we explain the necessary and realistic assumption of discreteness in assembly (or most any other type of) operations. Consider the following typical operation: 1: pick up bolt, 2. pick up nut, 3. insert bolt in hole, 4. start nut on bolt, 5. pick up tightening tool, 6. tighten nut on bolt, 7. put aside tightening tool. Clearly, there is a natural consecutive work relationship between these elemental tasks, such that they usually are performed most economically as an uninterrupted series. However, there is also a logical minimum "divisibility" of the elements of this task. For example, one operator "never" would be assigned the task of picking up the bolt and another the task of inserting it. Also, while an operator is picking up a bolt with one hand, often he also can pick up the nut with the other hand, etc. Similarly, larger assembly tasks often have technical requirements which makes it uneconomic to divide them continuously into arbitrarily short tasks in order to distribute over two or more operators. Hence, if any group of tasks is naturally connected, there is a loss-of-time penalty for dividing it. And, there is a minimum acceptable divisibility of any manual task.

The problem in assembly line balancing arises from the fact that the task performance times are determined as a function of their natural or logical divisibilities, yet the stations along the assembly line are composed of groupings of these operations with no a priori assurance that each station can be assigned a combination of operations for which the sum of the operation times is exactly, or even nearly, equal to the cycle time. Because the conveyor usually moves at a uniform speed there is ordinarily no opportunity to store the commodities between stations for allowing different cycle times at different stations. Hence, the assembly line balancing problem is to select a permutation of the tasks into an assembly sequence and a combination of the tasks into "stations" such that (a) the selected combinations of tasks satisfy the technological precedence relationships between the tasks, (b) the sum of task performance times assigned to every station is equal to or less than cycle time and (c) the sum of the idle times over all stations is minimum.

In a slightly more general situation, the problem also includes so selecting combinations of tasks into stations that the sum of wages paid over all stations is minimized. This problem arises out of the fact that often each operator is paid at the hourly wage rate at which the task with the highest pay rate in his set of assigned tasks is evaluated. Each task has a different pay rate based upon required skill, etc. In the problem studied here, the potential savings from this further refinement appeared to be insufficient to justify the additional study. In other cases it may be worthwhile.

[4] For persons not familiar with methods of determining work standards, it is mentioned that these standards already include allowances for certain delays, for fatigue, etc. The loss mentioned here is beyond these normal allowances.

[5] This point could be extended to touch upon the current, vigorous Industrial Engineering debate as to whether or not elemental tasks are independent in the sense that addition of their operation time values is, in general, commutative. We avoid that argument here by noting that dependence has been encountered, but that the advantage of a simplified model which assumes independence greatly outweighs the computational disadvantage of a model which includes dependence. Hence, the method used here essentially assumes that all combinations of tasks which result in an error due to non-commutativity of more than, say, five per cent are excluded from the set of admissable solutions. For a more general discussion of the problem see reference 9.

Notation

We now develop initial notation for a more formal statement and analysis of the problem.

Denote by:

- i, $i = 1, \ldots, I$, a set of objects called elemental assembly tasks. Each task is associated with assembling a particular component part to the commodity, or with a required process or operation.
- k, $k = 1, \ldots, K$, a set of objects called "assembly stations," each of which consists of a subset of one or more of the elemental tasks.
- t, a time measure on the production period. (In our study, the unit of measure is decimal hours.) Let there be 1, 2, 3, . . . , T units of time in the period.
- a_i, a number indicating the number of units of time as measured in t which is required to carry out the ith elemental task on one unit of the commodity being assembled.
- c, the cycle time of the assembly line as measured in number of units of time per unit of the commodity being assembled.
- q, forecasted number of units of the commodity to be produced and sold during the period.
- I, set of tasks, $i \in I$.
- I_k, the subset of tasks, i, which are elements of or assigned to station k.

Analysis of Problem

The cycle time for an assembly line is

$$c = \frac{T}{q} \qquad (1)$$

A necessary condition that an assembly line can be balanced within the cycle time is that $a_i \leq c$, $i = 1, \ldots, I$.

Proof of this concept is partially analytic and partially experimental. The analytical proof is, of course, self evident. The experimental proof lies in at least two now well accepted results.

1, if any task is divided into smaller tasks beyond a certain point, the sum of the times required to carry out the smaller tasks begins to increase rapidly and becomes much greater than the time to carry out the undivided task. This is because any task can be reduced to a set of logically discrete tasks which if arbitrarily divided further require additional elements of work to interconnect the elements of the divided task. These additional elements consume time and increase the work content significantly and it has been found by experience that a cycle time less than a specified length simply is inefficient for manual operations, especially in relation to boredom of the operators.

2, if any $a_i > c$, it would be necessary either to use two or more lines or two or more operators for that task. The latter often is unacceptable (at least in this study) because of operator training,[6] supervision, and other related difficulties.

[6]For example, these operators would learn at rates different from rates at which other operators on the line would learn.

The minimum possible number of stations for an assembly line is:

$$K_{min} = \min_{n} \left\{ \text{integers } n \;\middle|\; n \geq \frac{\sum_{i}^{I} a_i}{c} \right\} \qquad (2)$$

That is, we consider only solutions with discrete numbers of operators. Of course, the maximum possible number of stations, if

$$a_i \leq c, \; i = 1, \ldots, I, \text{ is } I.$$

One formulation of the objective in assembly line balancing is to minimize the total amount of idle time, f(t), in the stations on the line,

$$f(t) = \sum_{k} \left(c - \sum_{i \in I_k} a_i \right) k \qquad (3)$$

An equivalent statement of the objective is to minimize the number of stations on the line. That is, for any given set, I, of elemental tasks, $i \in I$, there is a fixed sum.

$$\sum_{i} a_i \qquad (4)$$

which we may term the total "work content."

Rewrite Equation 3

$$f(t) = Kc - \sum_{k} \left(\sum_{i \in I_k} a_i \right)_k,$$

where K is the number of stations.

Since

$$\sum_{k} \left(\sum_{i \in I_k} a_i \right)_k = \sum_{i} a_i$$

$$f(t) = kc - \sum_{i} a_i \qquad (5)$$

Inasmuch as c and a_i are assumed fixed, f(t) assumes its minimum when K is minimum (within limitations discussed later). Any balance with K_{min} stations is termed a "minimal balance."

It is not necessarily always possible to achieve a minimal balance. For example, if n of the tasks i have operation times greater than half the cycle time,

$$\left\{ n(i) \mid a_i > \frac{c}{2} \right\},$$

then the minimum feasible number of stations is at least n. We denote this number by K_{res}. Corresponding observations can be made respecting K_{res} when $a_i > \frac{c}{3}$, $\frac{c}{4}$, etc. The precedence relations between the tasks may increase further the minimum feasible number. For example, consider the following illustrative problem:

Let $c = 1.00$ (6)

and for $i = 1$ $a_i = .6$
2 $.7$
3 $.4$
4 $.5$
5 $.7$

Note:

(1) $a_i \leq c$, $i = 1, \ldots, 5$.

(2) $\frac{\sum a_i}{c} = 2.9$

(3) $K_{min} = \min_{n} \left\{ \text{integers } n \mid n \geq 2.9 \right\} = 3$

(4) $K_{res} = \left\{ n(i) \mid a_i > \frac{c}{2} \right\} + \left\{ \frac{n(i)}{2} \;\middle|\; a_i = \frac{c}{2} \right\} = 4$

By criteria established thus far, the actual number of stations required is:

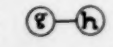
$$K = \max \{ K_{res}, K_{min} \} \geq 4. \qquad (8)$$

And, there would be the following four-station balances.

Balance (9)

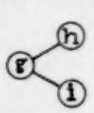
	No. 1			No. 2		
Station Number	(element)	(time)	idle time	(element)	(time)	idle time
1	(1)	(.6)	(.4)	(1,3)	(1.0)	(.0)
2	(2)	(.7)	(.3)	(2)	(.7)	(.3)
3	(3,4)	(.9)	(.1)	(4)	(.5)	(.5)
4	(5)	(.7)	(.3)	(5)	(.7)	(.3)
		Total 1.10			Total 1.10	

Now let us consider the effect of the precedence relations on the alternative arrangements of tasks into assembly stations. For this purpose, we develop the concept of a "precedence graph." It is as follows: whenever a task, say g must precede (be carried out earlier in time than) another task, say, h, write



(10)

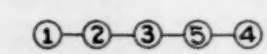
and read it "g must precede h." If two tasks are not ordered with respect to each other, we do not connect them with a direct line. For example,



(11)

would be interpreted "g must precede both h and i, but h and i are not ordered with respect to each other."

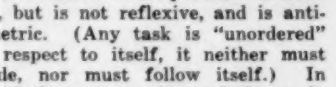
To demonstrate the effect of precedence relations on the above illustrative problem, consider a precedence graph as follows:

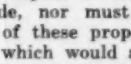


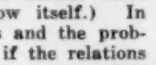
(12)

It is easy to see that both 4 station balances are excluded and the only possible balance is a five station balance.

In general, we wish to be able to balance assembly lines with much larger numbers of tasks, with arbitrary partially and linearly ordered precedence relations, and with arbitrary task work times. A first step in a practical problem is to analyze the precedence graph for consistency. In this regard we note that the relation "must precede" is transitive, but is not reflexive, and is antisymmetric. (Any task is "unordered" with respect to itself, it neither must precede, nor must follow itself.) In view of these properties and the problems which would arise if the relations should not be consistent in any practical context, the first requirement is to assure that there are no inconsistencies in the precedence relations, such as a precedence graph containing (1) both



(2) 

; (3) 

,

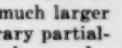
either directly or by successive application of the transitivity property.

Some of the additional requirements which a graph must satisfy in order to assure that it is not inconsistent include the following (a) every task appears once and only once, (b) every connecting line terminates at each end in at least one task, (c) by successive application of the transitivity principle it is not possible to exhibit any inconsistencies, such as in the foregoing paragraph, and (d) it is possible to number all tasks in the graph in such a manner that the numbers are assigned in ascending order from left to right along an unbroken relation line and it is never necessary to proceed from right to left along a relation line. Figure I is an example of a graph numbered in this manner and demonstrating a set of tasks and relations with no inconsistencies.

If a commodity has been manufactured, we know empirically that it is possible to draw its precedence graph free from inconsistencies. If any exist, it is due to the engineer and not the engineering of the commodity. For, if it were otherwise, an inconsistency would indicate a "which came first, the chicken or the egg?" situation, such that manufacture would be impossible. On the other hand, if a commodity previously has not been manufactured, it is conceivable that the engineering is poor and is made apparent by an inconsistent precedence graph.

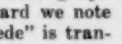
That a graph which satisfies the foregoing requirements is consistent is assured by Barankin's[7] consistency theorem (2) which is based on a precedence matrix as follows:

Let $P=(P_{ij})$ be a matrix of zeros and ones where

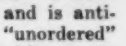
$P_{ij}=1$ if 

(13)

either directly or by successive application of the transitivity principle

$P_{ij}=0$ if 

(not ordered)



or if $i=j$

$P_{ij}=-1$ if

(anti-symmetric principle).

If our numbering and arrangement of the tasks in the graph satisfies the requirements specified earlier, then: where

(a) $i<j$ (above main diagonal), $P_{ij}=0$ or 1;
(b) $i=j$ (main diagonal), $P_{ij}=0$;
(c) $i>j$ (below main diagonal), $P_{ij}=0$ or -1,

and Barankin's consistency test is satisfied. (It should be noted that Barankin does not use the negative form of the "must precede" relation. However, we have found it useful here in practical applications. For the purpose of his test one needs only to substitute zero's for minus one's in the precedence matrix in order to obtain Barankin's matrix form.)

In order to demonstrate that the balancing problem can be reduced to a combinatorial, rather than a permutations, analysis, we now wish to prove that if we partition a consistent set of tasks into subsets (stations) so that the precedence relation between tasks in different subsets is satisfied, the precedence relations between tasks within any such subset also can be satisfied.

Suppose we partition the set I, of tasks $i_\epsilon I$ into three proper subsets, I_k, I_l, I_m, such that

$$I_k \cup I_l \cup I_m = I \qquad (14)$$
$$I_l \cap I_k = \emptyset$$
$$I_k \cap I_m = \emptyset$$
$$I_m \cap I_l = \emptyset$$

and such that every $i_\epsilon I_l$ has its immediate predecessor (s) $^*i_\epsilon I_k$ or I_l and its immediate successor (s) $i^*_\epsilon I_l$ or I_m. ($^*i$ must precede i must precede i^*). Now, if $^*i_\epsilon I_l$, we always can arrange the elements of the subset $\{i, {}^*i_\epsilon I_l\}$ in such manner that $^*i$ precedes i. If $^*i_\epsilon I_k$, we arrange so that I_k precedes I_l and hence $^*i_\epsilon I_k$ precedes $i_\epsilon I_l$. If i has two or more predecessors, the same reasoning can be applied. Indeed, the reasoning can be extended to consideration of i^* in relation to i and finally to i in relation to i^* and $^*i$, simultaneously. This exhausts the possibilities. (Of course, if i and $^*i$ or i^* are not precedence ordered, there is no problem.)

This result is intuitively expected. However, the reasoning might have been based, alternatively, on the precedence matrix. That is, by our partitioning rules, if the matrix P has +1's only where $i<j$, then the corresponding partitioned submatrices P_k, P_l, and P_m will have +1's only where $i<j$, and, hence, will be consistent; that is, the tasks can be ordered within each subset (station) in a sequence consistent with their set of precedence relations.

For the objective as stated in Equation 3, the problem now can be stated as follows:

$$\text{Minimize: } f(t)=\sum_{k=1}^{k}\left(c-\sum_{i=1}^{I} x_{ik}\,a_i\right)_k \qquad (15)$$

subject (a) to satisfying the precedence relations (b) to having each and every task assigned once and only once in the set of stations, and (c) the sum of operation times at any station being equal to or less than cycle time. That is; the solution is subject to the following.

(a) if any $P_{ij}=1$ and $i_\epsilon I_k$, then $j_\epsilon I_{k^*}$ or I_{k^*} where $k^*>k$ and the I_k are numbered in accordance with the same rules (left to right) for numbering the tasks i.

(b) $\sum_k x_{ik}=1$, $i=1, \ldots, I$

$$x_{ik}=\begin{cases}1 \text{ if task i is assigned to station k.}\\ 0 \text{ if task i is not assigned to station k.}\end{cases}$$

(c) $\sum_i x_{ik} \leq c$, $k=1, \ldots, K$.

An alternative objective and formulation of the problem is: For any given number of stations, K, select assignments x_{ik} of the tasks i to stations k so as to minimize the maximum total work time assigned to any station. That is,

Minimize:

$$\max_{c_k}\left\{c_k=\sum_{i=1}^{I} x_{ik}\,a_i,\ k=1, \ldots, K.\right\} \qquad (16)$$

subject to restrictions (a) and (b) of equation 15.

Computation

Our experience indicates that different computational procedures may be desirable for different conditions. That is, a set of "loose"[8] restrictions may prescribe one procedure whereas a set of "tight" restrictions may prescribe another. For example, a very loosely ordered set of assembly elements often can be handled by a procedure similar to those described in (11) paragraph 2A "Rapid Methods for the General (Assignment) Problem, not Necessarily Optimal," (Author's notes: that is, A Computational Procedure that is rapid but does not necessarily lead to an optimal solution. Word in parenthesis is authors.) Indeed the assignment problem

[7] Appreciation is expressed to Prof. E. W. Barankin for his assistance and interest in this problem.

[8] For convenience if a matrix P_{ik} has few +1's and many zeros we will say that the tasks are "loosely" ordered or is, simply "loose"; we say it is "tight" when it has many +1's.

may be considered to be a special case of the assembly line balancing problem in which

(1) $a_{ij}=c_j$; i=1, . . . , I
(2) $P_{ij}=O$: i,j=1, . . . , I
(3) I=K.

A "Tight" Situation often may be handled conveniently by procedures approaching exhaustive enumeration of possible combinations. In between these extremes other compromises may be necessary.

Two possible computational procedures will be given below. The first is based on given cycle time (rate of output) and the objective is to minimize wasted or unused operator time. The other is based on the second formulation of the problem and assumes a fixed or given number of operators (station). In it the number of operators is varied discretely over a range predetermined so as to span the desired rate of output. Then, at each integral number of operators within that range, a minimum maximum station work-time is found, and that number of stations selected which gives a cycle time or rate of production nearest[9] the desired rate of production. (It is obvious in this method that the station with the maximum total assigned work time is the "bottleneck" or limiting station and, hence, its work time becomes minimum cycle time for the entire line.)

Procedure 1:

The problem can be translated into a familiar mathematical model by a simple change in notation. Let $B=(b_{ij})$ be a matrix of entries O or 1 and indicating the following: O if an element i is not assigned to the jth column (vector), and, 1 if it is. Each column vector then is a combination of certain specified elements and as such we may consider it a "candidate" for becoming a station. Each such combination will have a characteristic delay or idle time denoted and defined here as

$$d_j=c-\sum_i b_{ij}\ a_i,\ j=1, \ldots, n. \qquad (17)$$

The problem then can be stated as

$$\text{Minimize:}\ \sum x_j\ d_j \qquad (18)$$

subject to

(1) $\sum_j x_j\ b_{ij}=1$, i=1, . . . , I
(2) $O \leq x_j \leq 1$, j=1, . . . , n
(3) $O \leq \sum_i b_{ij}\ a_{ij} \leq c$, j=1, . . . , n.

The restrictions in this formulation define a convex subset of an n-dimensional space, each point in which is specified by an n-tuple, $(x_1, x_2, \ldots, x_n)$. The extremes of that subset are those n-tuples in which (1)

$$x_j=\begin{cases} O \text{ or} \\ 1, \quad j=1, \ldots, n, \end{cases}$$

(2) for which the restrictions in 18 hold, (3) for every i there is exactly one $x_j\ b_{ij}=1$, all other $x_j\ b_{ij}=O$ for that i.

With this formulation, then, one seeks at least one extreme at which the functional, 18., is minimized. There are standard procedures available for this, i.e., Dantzig's simplex algorithm (4). Indeed we have used successfully the Project SCOOP, Department of the Air Force UNIVAC simplex routine for solving several small problems.

However, it should be noted that in order to obtain this convenient mathematical model, one must use a pre-enumerated matrix of feasible combinations which can be "enormously large," although due to the precedence and cycle time restrictions, the number may often be considerably reduced.

Of course, until much better computational facilities are more generally available, it is not possible for most persons to handle problems which are "large," using any presently available formal mathematical algorithm, such as the simplex method. It is expedient, therefore, to develop practical methods which usually will yield an optimal solution. The method which follows is such an expedient. It is based on the problem as stated in 18, except it does not require a matrix inversion routine. Since in order to represent the problem as one in a continuous variable makes it so large as to be unmanageable, we consider here a method in which the problem is in a discrete variable, i.e., as a combinatorial problem. However, we still endeavor to use methods that, within certain probability limits, assure that an optimum or minimum will be obtained. Also, we endeavor to have this method take advantage of the alert characteristics of the human mind in handling combinatorial problems of reasonable proportions. The method suggested here for this purpose handles the problem essentially by reducing the large combinatorial problem to several smaller problems, each of which is quite manageable on a systematic basis. Indeed, by extending these small problems, one eventually could include all the possibilities included in the large problem. However, we have found that it is seldom necessary to consider all possibilities, since there are many minimal solutions and at least one has been found in every case within a reasonable amount of time.

This method is as follows. It is illustrated later in reference to a small scale problem.

The method in theory operates as follows: A, the matrix B is enumerated. B, a "good' initial solution is obtained by selecting in any arbitrary manner a combination of "good' stations to comprise a balance. C, by testing different combinations of the stations which have been selected, one attempts to find better recombinations of the elemental tasks so as to improve the solution. This last step implies a series of small combinatorial analyses in lieu of a matrix inversion, such as in the simplex method. However, the combinatorial method may incorporate optimality tests which are conclusive at least within the set of combinations tested.

The steps in the method are as follows:

I Generate the Matrix, B

a. Select each individual task as one of the candidate combinations.
b. Generate selected combinations, B_j, such that

$$O < \sum_i b_{ij}\ a_i \leq c;\ j=1, \ldots, n.,$$

and such that the precedence relations are not, and cannot, be violated.

c. Record the combinations as in Table I, page 24.
d. Compute and record for each combination

$$d_j=c-\sum_i b_{ij}\ a_i;\ j=1, \ldots, n.$$

II To select a feasible balance:

a. Select the column, B_j, with minimum d_j. If a tie, arbitrarily select any one of those in the tie.
b. Write the selected column B_j in the solution matrix, e.g. $S=(s_{ij})$ Table II in the sample problem.
c. Select from among those columns in b which do not have any entry in any of the rows in which the column selected in step II(a) has entries, a second column again one with minimum d_j.
d. Write the second selected column into S as a second column.
e. Continue as in the foregoing, each time deleting from consideration those columns in B which have any entry in any row in which any of the columns already in S have entries, until every row in S has one and only one non-zero entry. The completed matrix S, at this step then constitutes an initial feasible solution or line balance.

III To Determine the Optimality:

a. Compute for the solution at this step,

$$D=\sum_{j \in S} d_j$$

1. If D<c, the set of combinations contained in S is an optimal combination and the computation is terminated.
2. If $D \geq c$, it may be possible to find some other combination which is better. Proceed to step IIIb.

b. If III(a)2, compute for each selected combination of columns in B a number,

[9] "Nearest" may be defined or determined by judgment or by statistical decision procedures.

$w^*_j = -\sum d^*_j + \Sigma d_i^*$,
where d_i^* are the d_i for those columns which are to be removed from S and the d^*_j are the d_i for those columns which enter S if the columns under consideration were removed from the solution.

1. If $w^*_j \leq 0$, the solution already in S is better than the others tried, and can not be improved by introducing any of those combinations into S.

2. If any $w^*_j > 0$, the solution in S is not optimal and a better solution has been found in the combination of candidates which yielded that w^*_j. Proceed to Step IV.

IV To Change the Solution:

a. Select the combination with maximum positive valued w^*_j (or any arbitrarily selected tie).

b. Enter that combination of columns into the solution matrix S and delete from S all columns which have a non-zero entry in any row in which the selected column has a non-zero entry. This will yield a new solution matrix S.

c. Return to Step III and Step IV in cycles until the criterion in either III(a) 1 or in III(b) 1 is satisfied, until all possible combinations have been tested, or until the engineer considers that the solution he has is good enough that further search is not warranted.

At the termination of computation, each combination of columns tested for which $w^*j = 0$ represents a set of candidate stations which, if entered into the solution, would give an equally good line balance. From a practical point of view, in relationships with the foremen of the assembly line, it is very convenient to have these alternatives since they permit him to chose combinations agreeable to him, but which do not destroy the optimality of the balance.

Of course, the foregoing computations seldom, if ever, need be made exactly as indicated because one seldom may not wish to enumerate the matrix. However, it illustrates the concepts underlying a more simplified practical, manual method which usually is of manageable proportions. To illustrate these concepts is important, especially in dealing with "practical' persons, because they easily may underestimate the magnitude of the combinatorial problem underlying the method and, hence, may adopt short cuts which could negate the value of any systematic method of analysis. Some of the simplifications in the method for manual handling are as follows:

Step I need not be enumerated.

Step II may be carried out by graphical methods., encircling each "good" combination to indicate a station until each element is included in one and only one station. The precedence requirements can be handled by excluding combinations of stations whose encircling lines cross or over lap (this simple requirement disposes of an otherwise "messy" logical problem).

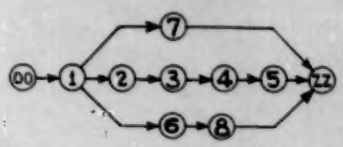
Step III should be carried out by selecting only combinations of stations in the solution which have idle time equal to or greater than cycle time, since an improvement in the balance can be achieved only by distributing the elements of two or more lightly loaded stations into a smaller number of efficient stations. This redistribution of the elements from the inefficient stations is accomplished by a combinatorial analysis of those elements to find another way in which they can be recombined into more efficient stations. In addition, it is necessary to consider the recombination of the elements from all possible combinations of the inefficient stations with all other (including the efficient) stations in the solution. If it were necessary, to consider the full set of such recombinations, the task would be equivalent to testing all possible combinations by exhaustive enumeration. Fortunately, it typically is possible to obtain minimal balances early in this procedure.

Step IV then becomes re-encircling the new combinations on the precedence graph, and changing the entries in the solution matrix

Let us consider the sample problem now to illustrate these computational procedures. Assume the following information: (we will not concern ourselves with adjusting c to c_∞.)

For i=1,	a_i=0.6	
2	0.4	
3	0.3	
4	0.4	c=1.0
5	0.2	K_{min}=4
6	0.7	
7	0.6	
8	0.5	
	—	
	3.7	

Figure I



Precedence Graph

	00	1	2	3	4	5	6	7	8	ZZ
00	0	(1)	1	1	1	1	1	1	1	1
1	-1	0	(1)	1	1	1	(1)	(1)	1	1
2	-1	-1	0	(1)	1	1	0	0	0	1
3	-1	-1	-1	0	(1)	1	0	0	0	1
4	-1	-1	-1	-1	0	(1)	0	0	0	1
5	-1	-1	-1	-1	-1	0	0	0	0	(1)
6	-1	-1	0	0	0	0	0	0	(1)	1
7	-1	-1	0	0	0	0	0	0	0	(1)
8	-1	-1	0	0	0	0	-1	0	0	(1)
ZZ	-1	-1	-1	-1	-1	-1	-1	-1	-1	0

Precedence Matrix

In the "precedence matrix" accompanying Figure I, the subset of relations designated by numbers in circles constitutes the "Minimal" set, and all others can be derived from them by the transitivity and anti-symmetric properties of the precedence relation.

Note that both the precedence graph and the precedence matrix demonstrate that the set of precedence relations is consistent. The full set of possible combinations for this problem is shown in Table I, page 24.

In Table I zeros are implied at all row-column intersections other than those with ones. Entries which are circled denote those with more than one station due to precedence consistency requirements. For example, it is consistent with the precedence relations and cycle time restrictions that elements 4 and 8 be combined in one column as a candidate for a station. However, if it were selected as a station it would create an inconsistency if another station were selected that included elements 5 and 6, which by themselves also constitute a permissible combination. Hence it is necessary to include, with elements 4 and 8 also element 6 by itself or in combination with an element that precedes element 4. The only such element with which 6 can be combined is 3, hence column 20 of Table I.

Table I—B=(b_{ij})

j=	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
d_j=	.4	.6	.7	.6	.8	.3	.4	.5	0	.3	0	.4	.3	.1	0	.1	.5	.4	0	.1	1.0	.2	.3
i=1	1								1						(1)								
2		1							1	1	1	1			(1)						(1)		
3			1							1			1	1	1	1	1			(1)	(1)		
4				1									1	1				1	1	1	(1)		
					1									1				1			1	1	1
6						1						(1)			1		(1)			(1)	1		
7							1				1					1			1			1	
8								1				1					1			1			1

Cycle I:

Step II Choose Feasible Balance

Table II; S=(S_{ij})

j	=9	19	23	3	6
d_j	=0	0	.3	.7	.3
i=1	1				
2	1				
3				1	
4		1			
5			1		
6					1
7		1			
8			1		

Step III Determine Optimality

a. D=1.3>c, therefore continue to IIIb.

b. Compute w^*_j for recombinations of elements from combinations of stations whose total idle time is greater than cycle time.

Stations Removed	Idle Time	Elements	Candidates	Idle Time	w^*_j
$^*j$=23 d^*_j=.3 i=5,8 j^*=none d_j^*—					
3	.7	3			
	1.0				—
3	.3	3			
6	.7	6	15	0	
9	.0	1,2			
	1.0			0	1.0
3	.3	3	20	.1	
6	.7	6	22	.2	
19	0	4,7			
23	.3	5,8			
	1.3			.3	1.0

etc.

Both of the last two combinations reduce idle time by 1.0 cycle time and both are successful in creating minimal solutions, as follows:

Step IV Minimal Solutions

	A				or			B
j=	15	19	23		j=	9	20	22
Σd_j	0	0	.3=0.3		Σd_j=	0	.1	.2=0.3
i=1	1				i=1	1		
2	1					2	1	
3	1					3	1	
4		1				4	1	
5			1			5		1
6	1					6	1	
7		1				7		1
8			1			8	1	

Cycle II:

Step III

a. D=0.3<1, therefore solution is optimal and computations may terminate.

b. All W^*_j may be computed in the general case in order to determine other equally good alternatives.

From the two solutions, we obtain the line balances given in Table III.

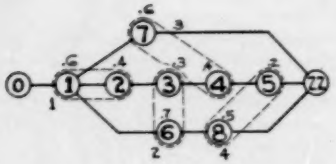
Table III—Line Balances

Station	No.	Elements	Total Assigned Time
A	1	1,2	1.0
	2	3,6	1.0
	3	4,7	1.0
	4	5,8	0.7
B	1	1,2	1.0
	2	3,6	1.0
	3	4,8	.9
	4	5,7	.8

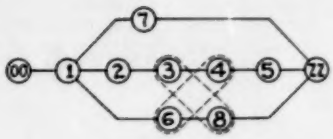
The suggested further abbreviation at this procedure is as follows:

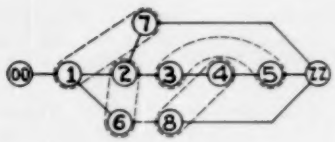
Step I—Omit

Step II—Prepare precedence graph including, also, the operation time values for the elemental operations. For convenience, express these times as precentages of cycle time.



Step III The solution obtained in the foregoing is already optimal. At this point, it is convenient to indicate some specific configurations which must not be used in selecting combinations of elements for becoming stations by this method:





ALTERNATIVE PROCEDURE

A second procedure has been suggested by Bryton (3). It follows essentially the concepts mentioned earlier as having been developed by Votaw and Orden (11) for rapid but not necessarily optimum solution of the Assignment Problem. However, Bryton's procedure incorporates a good technique for handling the precedence relation problem not present in the Assignment Problem. One of the advantages of Bryton's method is that it assumes a fixed number of stations and seeks to minimize delay time. Since this is equivalent to minimizing the maximum station time, it fits the second formulation 16 and related discreteness in number of personnel on an assembly line very nicely.

Some limitations on that method, however, are that (a) it tends to be susceptible to restricted optima and must be arbitrarily perturbed, (b) it does not handle a problem with highly restricted precedence relations well because it involves excessive checking (although the checking is rapid if carried out by large scale computer.)

Other Suggested Procedures:

A random, but rapid, search was used in a few cases and found to yield acceptable solutions in reasonable lengths of time. A search using information generated at each step might have considerable merit.

A method employing only logical operations has been considered but not tested. It would involve classifying the tasks into subsets according to character-

istic tasks operation times. Then, in conjunction with manipulation of the precedence relations (which involve only logical operations) a set of solutions could be sought.

Summary

When the study of this problem was undertaken it was presented as a permutations problem, hence a very difficult situation to handle. While the desire to handle as a problem with continuous variables is strong, no reasonable method thus far has been found which has immediate practical value. However, the dimensions of the problem have been significantly reduced, in part by making it combinatorial instead of permutations i.e., by the proof that any assignment of tasks to stations such that if the relations between the tasks in one station and the tasks in all other stations are satisfied it is always possible to develop a consistent ordering of the tasks within that station.[10] Then, by considering the set of solutions as a convex subject of a high dimensional space, one gains the advantage of being able to move from extreme to extreme with a consistent "sense of direction." However, unlike problems whjch are not strongly discrete, a combinatorial analysis instead of a partial matrix inversion thus far has been used in practice to select the moves. This method is being explored for further application to fabrication scheduling where a similar representation of the problem is possible, but with a further convex subset at each extreme which must be explored before moving to another.

In any case, it is emphasized that there are many important problems to solve beyond the formal mathematical problems. Leadership and motivation by the foremen and supervisors are, of course, necessary. Interestingly, it is reported by operating personnel that the closely balanced assembly lines have acted as "100 per cent inspection" stations. No longer is there slack time available for "touch up" work on the assembly line that should be done in fabrication. The result of such improvements in line balance is, therefore, to diffuse the high quality levels which are maintained in assembly back to the source of quality control, i.e., fabrication and fabrication inspection.

Finally, the Engineers in the Method and Wage Rate Unit have obtained balances with so little idle time that some difficulty has been encountered because of increased frequency of operator failure to meet the cycle time. The reason for this difficulty is, of course, that all production rates or standards are really distributive, although they are treated in all motion-time systems as deterministic. Accordingly, a further refinement is to measure experimentally the other relevant parameters of each assembly task's distribution. At this writing, it appears certain that the present single parameter system (mean) for motion-time systems is not meaningful for refined methods of programming. Instead, we shall need at least a two parameter system (mean and variability) for short "stable" periods, together with regression coefficients or other measures of change in relation to such factors as quality of parts and tools, ambient temperature, season, hour of day, day of week, etc. Given these, it would be possible to develop a procedure whereby standard task time is flexibly established so as to yield optimum percentage of the time which the worker should be unable to meet cycle time. This is an optimizing problem because of opposing cost trends; i.e., attempts to assure 100% achievement of tasks will increase cycle time to uneconomic proportions; and, arbitrarily reducing cycle time (or increasing worker assignment) will result in excessive numbers of partially complete commodities having to be finish-assembled in the repair stations. New standard data together with a related computational method for finding the optimum compromise between these two opposing cost trends now are needed.

[10] For example, in a loose problem with 100 elements, the number of solutions would be in the order of magnitude of 100! But as a combinatorial problem it would be $100! \sim 1 \times 10^{8}$, a $5^{795} =$ relatively small number which would be made smaller by any precedence relations which may exist.

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Book Reviews

"Mathematical Thinking in the Social Sciences"

edited by Paul F. Lazarsfeld, The Free Press, Glencoe, Illinois, 1954, 444 pages, $10.00

The Industrial Engineer has traditionally been interested in the problems of coordinating men, materials and machines. The quantitative analysis of materials and machines has presented little difficulty, but quantification of men or the human factor has been questionable. Those interested in approaching this important area will welcome this compilation by many experts in the field. Numerous examples of using the "model" approach to develop better theoretical and practical understanding are presented. An excellent book for the advanced Industrial Engineer.

"Manual of Industrial Engineering Procedures"

edited by John A. Patton; Wm. C. Brown Co.; DuBuque, Iowa; 1955; $10.00

The stated purpose of this book is "to provide a working digest of step-by-step procedures for the ten essential programs for better management controls." This has been done. The outlines can furnish valuable guides for installing and maintaining programs in cost control, inventory control, employee training, personnel selection and testing, layout, materials handling, job evaluation, production planning and control, sales and distribution analysis, and wage incentives. The presentations are likely to give the inexperienced practitioner a false sense of security—which can be dangerous. The restricted area coverage is disappointing, for many areas of Industrial Engineering have not been included.

QUEUEING THEORY

By William T. Morris

Instructor, Department of Industrial Engineering, Ohio State University

The group of models often referred to as "queueing theory" have a number of interesting features which make them potentially useful to the Industrial Engineer. Here a brief presentation of some of the basic aspects of these models will be attempted, together with some indication of the method of application to industrial problems. Queueing theory has been used in the study of such physical processes as:

a. aircraft waiting to land
b. motor vehicle traffic
c. machine breakdowns
d. telephone traffic, etc.

These models generally describe the following characteristics of a process:

a. an input—"customers" are arriving
b. a queue discipline—for example customers may wait their turn on a first-come-first-served basis
c. a service mechanism—customers are "served" and thus removed from the waiting line.

Consider people lining up to buy tickets at a theater. We shall say the system is in state E_n if there are n people waiting to be served (including the person actually in the act of making a purchase). Forgetting about the service mechanism for the moment, the system goes to a state E_{n+1} when another person arrives in line. If we can think of these arrivals as occurring at random points in time, we are dealing with a stochastic process. (!!..the mathematical abstraction of a real process whose development is governed by probabilistic laws." [1]) We will be interested at first in processes which have the following properties:

a. they are subject to instantaneous changes of state which can occur at any time
b. these changes are due to random events
c. the process is stationary in the sense that the forces which govern it remain constant
d. future changes are independent of past changes.

From an intuitive consideration of the process we will formulate the following postulates:

1. The probability of one arrival in an interval of time Δt is proportional to the length of the interval—say $\lambda(\Delta t)$.
2. The probability of more than one change is $\propto(\Delta t)$ where $\propto(\Delta t)$ is an infinitesimal of higher order than Δt.

Now let $P_n(t)$=probability that n arrivals occur during the interval o, t. Consider $P_n(t+\Delta t)$—this event can occur in three mutually exclusive ways:

1. n changes during o, t; no changes during Δt.
2. n-1 changes during o, t; 1 change during Δt.
3. n-x changes during o,t; x changes during Δt.

The probability of each of these events is:

1. $P_n(t)[1-\lambda(\Delta t)- \propto(\Delta t)]$
2. $P_{n-1}(t)[\lambda(\Delta t)]$
3. $P_{n-x}(t)[\propto(\Delta t)]$

Using the addition theorem:

$$P_n(t+\Delta t)=P_n(t)[1-\lambda(\Delta t)-\propto(\Delta t)]+P_{n-1}(t)[\lambda(\Delta t)]+P_{n-x}(t)[\propto(\Delta t)]$$

Transposing and dividing by Δt

$$\frac{P_n(t+\Delta t)-P_n(t)}{\Delta t}=P_n(t)\left[\frac{-\lambda(\Delta t)-\propto(\Delta t)}{\Delta t}\right]+\frac{P_{n-1}(t)[\lambda(\Delta t)]}{\Delta t}+\frac{P_{n-x}(t)[\propto(\Delta t)]}{\Delta t}$$

Letting $\Delta t \to o$

$$\frac{dP_n(t)}{dt}=-\lambda P_n(t)+\lambda P_{n-1}(t)$$

For n=o this reduces to:

$$\frac{dP_o(t)}{dt}=-\lambda P_o(t)$$

This is a differential equation of the form $\frac{dy}{dx}=ky$, whose solution is $y=Ae^{kx}$.

Thus $P_o(t)=Ae^{-\lambda t}$ but $P_o(o)=1=A$;

therefore $P_o(t)=e^{-\lambda t}$.

Now for n=1

$$\frac{dP_1(t)}{dt}=-\lambda P_1(t)+\lambda P_o(t)=-\lambda P_1(t)+\lambda e^{-\lambda t}$$

This is of the form

$$\frac{dy}{dt}=-\lambda y+\lambda e^{-\lambda t}$$

with solution

$$y=e^{-\lambda t}\{\int(\lambda e^{-\lambda t}\cdot e^{\lambda t}\,dt)+c\}=\lambda t e^{-\lambda t}+C=P_1(t)$$

For t=o, $P_1(o)=o$ thus C=o

This gives

$$P_1(t)=\lambda t e^{-\lambda t}$$

But this is a Poisson Distribution with mean λt. This rather interesting result may be stated in the following way:

"We may expect the number of occurrences of an event during a given period to be distributed according to Poisson's law if the probability that the event occurs in an infinitesimally short period Δt is proportional to Δt, and the events are independent of one another." (2)

Now let us generalize the model in two ways. First, drop the assumption of independence and assume that if the system is in a state E_n the probability of going to E_{n+1} (an arrival is $\lambda_n(\Delta t)$. For every state we have a λn instead of a single constant. Further, assume that the system can go from E_n to E_{n-1} (if $n \geq 1$) corresponding to a departure.

The probability of a single departure when the system is in a state E_n is $\mu_n(\Delta t)$ and the probability of more than one departure is $\propto(\Delta t)$ where $\propto(\Delta t)$ is of smaller order of magnitude than Δt. Now using the method demonstrated above we obtain the following equations:

$$\frac{dP_n(t)}{dt}=-(\lambda_n+\mu_n)P_n(t)+\lambda_{n-1}P_{n-1}(t)+\mu_{n+1}P_{n+1}(t) \quad \text{For } n \geq 1$$

$$\frac{dP_o(t)}{dt}=-\lambda_o P_o(t)+\mu_1 P_1(t) \quad \text{For n=o.}$$

These are the fundamental equations of the "Birth and Death" process. The coefficients λ_n and μ_n can be specified arbitrarily and the above equations together with the initial conditions of the system will give an unique set of probabilities, $P_n(t)$. The general method of applying the model consists of specifying a set of coefficients to describe a particular situation.

After a long period of time the systems we have described settle down to steady state or equilibrium conditions. The steady state is characterized by the limits:

$$\text{As } t \to \infty \text{ Lim } P_n(t)=p_n$$

which exist and are independent of the initial conditions (the number of people in line at t=o). This implies that:

$$\frac{dP_n(t)}{dt} = 0$$

Rewriting our basic equations for the steady state we obtain:

$$(\lambda_n + \mu_n)p_n = \lambda_{n-1}p_{n-1} + \mu_{n+1}p_{n+1} \quad \text{For } n>1$$

$$\lambda_o p_o = \mu_1 p_1 \quad \text{For } n=o$$

Many of the problems of interest involve equilibrium or steady state conditions. We may now state the general method of using these equations:

1. specify the λ_n and μ_n
2. calculate p_o
3. by successive substitution calculate $p_1, p_2, - - - -$
4. if possible find an expression for the general term p_n
5. from this the mean and variance may be obtained.

Let us consider as a simple example the case of men lining up at a tool room window. Let us suppose that the initial observations lead us to assume that arriving traffic may be described by a Poisson distribution with mean λt and that the departing traffic has a similar distribution with mean μt. The system may then be characterized by the following specifications:

$$\lambda_o = \lambda \quad \mu_o = 0$$
$$\lambda_n = \lambda \quad \mu_n = \mu$$

Substituting in the basic equations developed above and passing to the steady state condition it may be found that the probability of n men waiting at the tool room is given by

$$p_n = (\lambda - \mu)\frac{\lambda^n}{\mu^{n+1}}$$

Now it will be seen that unless $\frac{\lambda}{\mu} < 1$ this expression has no meaning. For finite n the probabilities will all be zero and the line will gradually grow beyond all bounds. This, of course, merely means that the mean service rate must be greater than the mean arrival rate, which is as would be expected. For n equal to zero this equation reduces to:

$$p_o = (1 - \frac{\lambda}{\mu})$$

which is the probability that the tool room attendant will be idle. The expected number of men waiting in line is found to be:

$$E(n) = \frac{\lambda}{\mu - \lambda}$$

From this equation the effects of changing the number of tool room attendants or the method of service may be assessed by substituting the appropriate value of μ. The variance may be computed with the following result:

$$\delta_n^2 = \frac{\lambda\mu}{(\mu - \lambda)^2}$$

From this a control chart might be constructed to detect changes in the system means, which might be traced to such assignable causes as tool shortages, improper usages necessitating more frequent replacements, and the like. In some cases it is necessary to make it a policy that no more than N persons shall be waiting at the tool room at a given time. By making the following changes in the system parameters we may find the probability that the line will be "full":

$$\lambda_n = O \quad \mu_n = O \quad \text{For } n>N$$
$$\lambda_n = O \quad \mu_n = \mu \quad \text{For } n=N$$

$$p_n = \left(\frac{\lambda}{\mu}\right)^n \frac{1-\frac{\lambda}{\mu}}{1-\left(\frac{\lambda}{\mu}\right)^n}$$

Other types of problems which have been attacked by this method include:

1. A set of m machines which are subject to breakdown and are to be serviced by r<m workers.

$$\lambda_o = m\lambda \quad \mu_o = o \quad \text{For } n=o$$
$$\lambda_n = (m-n)\lambda \quad \mu_n = n\mu \quad \text{For } 1 \leq n \leq r$$
$$\lambda_n = (m-n)\lambda \quad \mu_n = r\mu \quad \text{For } r \leq n \leq m$$

2. A feed back control scheme of servicing where the service rate is made proportional to the length of the line.

$$\lambda_o = \lambda \quad \mu_o = o \quad \text{For } n=o$$
$$\lambda_n = \lambda \quad \mu_n = n\mu \quad \text{For } n \geq 1$$

The solutions to these and other problems are given in Feller. (3)

Another quantity of interest is the mean time which a customer must wait for service. In the case of the single waiting line with poissonian input and service mechanisms this may be obtained as follows:

In the steady state let:

q=the number of people in line when the i th customer departs

q'=the number of people in line when the i + 1 st customer departs

r=the number of arrivals while the i + 1 st customer is being served

$$\delta = \begin{cases} 1 \text{ if } q=o \\ o \text{ otherwise} \end{cases}$$

Note that

$$q' = q - 1 + \delta + r$$
$$\delta^2 = \delta \quad q(1-\delta) = q$$
$$E(q) = E(q') \quad E(q^2) = (q'^2)$$

If v= service time of the i+1 st customer,

$$E(r) = \lambda E(v) = \frac{\lambda}{u}$$
$$E(\delta) = 1 - E(r) = 1 - \frac{\lambda}{\mu}$$

Squaring the expression for q';

$$q'^2 = q^2 - 2q(1-r) + (r+1)^2 + \delta(2r-1)$$

Taking expected values;

$$E(q) = \frac{E(\delta)E(2r-1)}{E(2[1-r])} + \frac{E(r+1)^2}{E(2[1-r])} = \frac{E(r^2) - E(r)}{E(2[1-r])} + \frac{\lambda}{\mu}$$

Now noting that:

$$f(r) = P_{\frac{r}{v}}(v) = e^{-\frac{1}{\mu}v} \cdot \frac{\lambda v}{\mu} \cdot \frac{(\lambda v)^r}{r!}$$

$$E(r) = \frac{\lambda}{\mu} \quad E(r^2) = \frac{\lambda}{\mu} + 2\left(\frac{\lambda}{\mu}\right)^2$$

$$f(v) = \frac{1}{\mu} e^{-\frac{v}{\mu}} \quad E(v) = \frac{1}{\mu} \quad E(v^2) = 2/\mu^2$$

Substituting;

$$E(q) = \frac{\lambda + \delta v^2 - \left(\frac{1}{\mu}\right)^2}{2\left(\frac{1}{\lambda}\right)\left(\frac{1}{\lambda} - \frac{1}{\mu}\right)}$$

If a departing customer leaves q persons behind him, and his own service time and waiting time are v and w respectively then q is the number of arrivals during w + v.

$$E(q) = \lambda[E(w) + E(v)]$$

From this and the above we can obtain:

$$\frac{E(w)}{E(v)} = \frac{\frac{\lambda}{\mu}}{\propto \frac{(1-\lambda)}{\mu}} [1 + \mu^2\delta v^2]$$

This is known as the Pollaczek-Khintchine formula. (4)

Returning to the example of men waiting at the tool room, we can now note the effects of changes in the system parameters on the mean waiting time. If the service time could be made perfectly regular, that is the variance reduced to zero, the mean waiting time could be reduced to one half of its present value under our assumption of a Poisson Distribution. Also, of course, a reduction in the mean serving time would reduce the expected wait in line.

Another interesting example is that of two parts which arrive at an assembly point in a production process. If part A arrives and no part B is waiting to be assembled, a bank of part A forms. Likewise if a B part arrives and no A part is available, a bank of B's starts. Suppose one can assume that the parts arrive in independent Poisson streams with mean arrival rates, a and b, and that a and b are equal. The expected bank size of either A or B is then given by:

$$E(n) = at - bt = 0$$

Thus the mean size of the bank is what one would probably desire. However, the variance of the distribultion of the number of A's or B's is as follows:

$$\delta_n^2 = at + bt = (a+b)t = 2at$$

This will be seen to increase indefinitely with time. As the process develops larger and larger banks of parts will occur.

A complete bibliography of the literature on the theory of queus is given in Kendall (4).

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PRESIDENT'S MESSAGE

(Continued From Page 2)

family and it is fair to expect that we shall grow in many ways as a result of such participation.

As a part of a program to have high level conferences wherein the problems, techniques and objectives of Industrial Engineering can be presented and discussed, two Regional Conferences have been held. Also several senior chapters have played host to conferences which have been highly successful in both content and attendance. Such events are most beneficial in arriving at common objectives for the profession. The response to these meetings indicates a growing interest in our profession which should be even greater in the ensuing years. Papers presented at these meetings and publication of proceedings of the meetings will become important contributions to the literature of the profession and in my opinion should be encouraged.

In our editorial program much attention has been given to provocative and philosophical problems of the profession. The objectives of our profession are thus seriously being discussed and as a result much introspective thinking is occurring. Changes in curricula design are occurring which reflect newer design areas in Industrial Engineering. Industrial Engineers are gradually—perhaps a little too much so—beginning to recognize their responsibilty in writing articles concerning their methodologies and successes in solving managements' problems. Our publishing media contribute most heavily in defining and explaining Industrial Engineering. Support of this activity should be encouraged and increased at every opportunity.

During the year many nationally known engineers and managers have become members of A I I E. This added energy and counsel is already being felt in many ways. With such assistance the future of the profession is assured.

In closing I should like to offer my heartfelt thanks to the officers, directors, committee chairman and our office force which have provided the effort and enthusiasm so necessary to the real progress which has been made. Looking to the future, and judging from the calibre of our new officers which will be installed in St. Louis, it is obvious that 1955-1956 will be an even better year.

EMPLOYEE MOTIVATION

(Continued from Page 5)

you go to the automatic factory. What then? You will still have many people employed. People spend money, only people can save it. Systems won't do it for you.

Much of the money that people spend is their time. We call this wages and salaries. According to Heron, our job is to sell this time at prices customers are willing to pay. Will your customers pay for wasted time? Will they pay for inefficiencies? Will they pay the costs of the "one big happy family?" Will they pay for losses of people who conform rather than perform?

It seems to me that to survive and prosper we have to reduce and control costs. To do that, I think we have to know what is a fair day's work. I believe strongly that we have to sort out our management errors. I'm sure that we have to know where our cost leaks are. I'm certain that we should know where our profits are made or lost. How can we get those facts without work measures? How can we get people to turn out a day's work unless we tell them how much that is?

MAXIMUM OUTPUT

But a fair day's work is only a fair output. That is perhaps 20 to 25 percent less than you can get on the average with incentives. A fair day's work is much less than your best people can turn out. To get better than average output, I think that you must use some method that rewards those that turn out more than average output.

Here is an example that may illustrate the point. It is taken from "The Practice of Management" by Peter Drucker (p.151). Peter Drucker cites the case of a big pharmaceutical company with an annual bonus that failed to reward individual performance. He points out that a senior chemist made a discovery affecting the whole field of organic chemistry. This would take several years of hard work to turn into commercial products.

During that same year, the big bonus went to the man who had made several small and easily salable improvements. Drucker's closing line is, "The man who made the discovery quit and so did four or five of his colleagues—altogether the best chemists the company had. It still has difficulty recruiting first-rate research men."

You cannot survive and prosper that way. You must try to get the best performance from each person in your organization. My conclusion is to set up measures of performance that are carefully adjusted for "management errors."

Finally, reward those who perform. In so doing, I would avoid group averages in order to develop the best in each individual. So I urge you to reward your outstanding people with extraordinary rewards.

STATISTICAL MODEL

(Continued from Page 7)

(8) Find and graph the sample regression curve (least squares

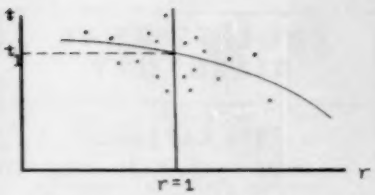

Figure 1. Standard Time=at_1

curve) on the scatter diagram.

(9) Locate the point $(1, t_1)$ of intersection of the regression curve and the line $r=1$.

(10) Multiply the t coordinate t_1 of this point by the allowance factor a obtained from a separate ratio-delay study.

Figure 1 illustrates the above method.

Conclusion

The initial results of this investigation have been presented in the hope that they may stimulate further analysis of this and other phases of work measurement.

It is recognized that deviations from the prescribed steps may be necessary in practice. For example, a large number of sample points, though desirable for high reliability of the estimate, may involve excessive cost. Nevertheless, the intent has been to develop a statistically sound technique to estimate standard time.

It should be noted that the proposed model replaces the narrow definition given in equation (2), where the speed rating factor r multiplies the observed time t, by the more general notion of relating r and t by means of the pair (r, t). Thus performance rating could be used instead of speed rating provided normal performance is first defined. In any case, the relation between r and t, as reflected by the scatter diagram, need not be linear. Thus the proposed statistical model has the advantage of being more general, in addition to being more realistic.

INVENT A PROFESSION

(Continued from Page 9)

So there's your program. Ah, but haven't we overlooked one thing We should give this blueprint a name, shouldn't we? A couple of good workaday words that will make a striking combination. How about Profession Synthesis? And of course we'll abbreviate that to P. S.

But that's only your affirmative program. You'll need to prepare a defense, too. The skilled strategist looks both ways. Not that you need have any apprehension about industrial executives. They'll buy it. You can be assured of this when you read that "Few executives felt they understood the highly complex and technical nature of O. R.", yet nevertheless, "In general the feeling is that operations research is becoming an integral part of progress in business."[20]

[20]Caminer and Andlinger, ibid., pp. 134, 136.

No; but some snide member of a competing profession (you can't keep on inventing professions without getting some overlapping) may take a potshot at you. You must be prepared.

Suppose it is suggested that the operating man ought to be encouraged to do his own thinking rather than have someone else do it for him; suppose it is suggested that doing his thinking for him "constitutes a threat to the initiative of the operating personnel."[21] Well, your answer to that one is plain enough. You will say that the operating man has had his chance to do his own thinking, and he hasn't done it, so he should get out of the way and let somebody think who can and will — and, besides, he couldn't ever do your kind of thinking anyhow.

Then suppose your critic comes back with the query, Well, is there a new kind of thinking? Don't you still get the facts, appraise them, and reason from them to a conclusion? Have you got a different way of thinking?—Here you must be gentle with your heckler, and, if you pity his innocence, don't show it too much. Just tell him he probably won't understand, but you do your thinking with probabilities and binomial distributions and sensitive parameters, plus a dash of electronic computing. Better go easy on sampling because he may know something about that.

Now you are at a danger point. Chances are your cynic will rally with the suggestion that that sounds like mathmatics to him, and isn't this new concept of yours just a greater use of mathematics? and why not let the operating man do all the thinking his experience and training qualify him for, and you just offer your assistance as a mathematician? This is a canard that must be squelched immediately, for it strikes at the very foundation of your new profession. Repudiate any suggestion that your profession has any affiliation with market research, quality control, industrial engineering, statistics—or common sense. Be a little indignant if it is called a new sales or product gimmick. Leave no doubt that "In truth, operations research is none of these thing."[22]

If the doubter still doubts, it is now time to become austere. You must make an appeal to the man's instinct of conformity. Manage your answer something like this: "Management must also, at times, have an almost implicit faith in the ability of the operations analyst. This faith will come easier once management gains more knowledge of the new tool."[23] You can be sure this will hold him, and you won't have to explain how he can get knowledge by relying on faith.

Your greatest danger, however, will come from yourself—from the still voice within you. You may hear it whisper, What ever happened to Technocracy? Pay no attention. You have one abiding assurance. Even if you have nothing new but a name, still, if it's talked about enough, you'll make some of those old mossbacks sit up and think a little more before making their snap decisions.

Now you're all set.

Good luck!

[21]Miller, ibid., p. 130.

[22]Hermann and Magee, ibid., p. 100.

[23]Caminer and Andlinger, ibid., p. 134.

A REPLY

(Continued from Page 9)

Now we calculate the efficiency of this straight-line layout as Smith would do it. X is found to be 600 weight units x 1 distance unit + 500 weight units x 2 distance units or 1600 weight-distance units.

$$E = \frac{1100}{1600} \times 100 = 69\%$$

By rearranging the table to A C D B, X will drop to 1400 and E will then be raised to 78 per cent.

But why confine ourselves to this unrealistic linear layout as shown below to the left? By using the right hand diagram we can present a schematic layout which gives a more satisfactory basis for determining X.

A C D B

A B
C D

We can consider all the movement from A to B, then B to C, etc., and set up the calculation for X as follows:

$$X = \underset{\text{A to B}}{(100 \times 1)} + \underset{\text{A to C}}{(200 \times 1)} + \underset{\text{B to C}}{(100 \vee 2)} + \underset{\text{C to D}}{(400 \times 1)} + \underset{\text{D to B}}{(300 \times 1)}$$

$$X = 1141$$

$$E = \frac{1100}{1141} \times 100 = 96\%$$

The only "inefficient" movement is seen to be the movement of 100 weight units from B to C (1.41 distance units, or .41 distance units more than the minimum possible). If diagonal aisles are not allowed, we would have a distance of 2.0 units between B and C, which would lower our efficiency slightly.

In conclusion, let me say that travel charts are of great value in helping the layout engineer decide which department should go where in a process-type layout. If Mr. Smith's type of layout efficiency index is desired, however, make a schematic floor plan to determine distance units—don't count squares in a table. If greater refinement is desired, make a rough area allocations to scale and scale off distances. Let's not be confied to straight-line layouts!

THE CRITERIA

(Continued from Page 17)

the consumer desires. Here, again, it should be stated emphatically that the mere fact that this interdependency of the three areas of engineering is not fully recognized and exploited in school

and industry does not change this conclusion.

8. The basic pattern governing analysis, synthesis, and evaluation of any engineering problem must therefore be as follows:

Alternatives	Function	Quality	Cost	Date	Other
A					
B					
C					
D					
Etc.					

Whether we are trying to determine which one of a number of alternative materials to select, or which one of a number of alternative production methods to select, or which one of a number of product designs to select, etc., the basic mode of analysis suggested by the above pattern must be followed.

Experience indicates that it is very likely that the alternative which satisfies best the interests of the Product Design Function is not the one which satisfies the Process Design Function to the best advantage, and further that the best alternative from the viewpoint of the Schedule Design Function can be different from the other two. Who is to decide which alternative is to be selected? It can be seen that the decision must be based on consumer preference manifested through the Marketing Function, and not in terms of the dictates of anyone of the design functions of engineering, for each has its own axe to grind. It will be recognized that the selection of one alternative from those generated by the design functions presents a problem upon which the tools of the newly emerging management science can be put to use effectively.

Conclusion

The need for intensive and objective study of the specific nature and criteria of engineering is not only serious, but imperative on college campuses and in industry.

The "ferment" in engineering education will, undoubtedly, produce many new curricula. What shall be the criteria for evaluation of what is fundamental to engineering? Will these criteria be based on the traditional American goal of harnessing the materials and forces of nature for the *use* of mankind or will they be based on the goal which has characterized engineering in many other parts of the world, namely, making something *available to mankind?* Gaging curricula merely in terms of their being "analytical" and "fundamental" does not answer this question. There still remains the question, *"for what?"*

In industry, too, there is need for evaluation of engineering against the criteria of engineering. While lip service may be given to the importance of collecting the "dollar votes" of the consumer, recognition of the three functional areas of design on an equal rank basis is far from being a fact. One of these areas of design is the most poorly coordinated function of any of those that comprise the organization structure. The improper use of engineering talent in industry was mentioned early in this paper.

So what? A lot of diligent study, analysis, and synthesis lies ahead. A good start can be made with the references which follow.

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◆ BOOK REVIEWS ◆

"Human Engineering Guide for Equipment Designers"

by Wesley E. Woodson, University of California Press, Berkeley 4, 1954, 266 pages, $3.50

This book should be available to every Industrial Engineer who does any design work. In fact, it should be available to every individual engaged in design work. It is an outgrowth of research executed for the Sonar Systems Branch of the Electronics Design and Development Division, Bureau of Ships, U.S.N. The information was published because it was felt that such a compilation would materially aid engineers in designing their equipment from the human-operator standpoint. We should be grateful that these data have been made generally available.

Written for the Industrial Engineer, the equipment designer, the industrial psychologist, and the systems engineer, this book presents the latest available data. Recommended design practices in instrumentation, work spaces, illumination, fatigue, acoustics, temperature, and ventilation are described, with check lists for specific factors. A second section discusses fundamentals of visual and auditory capacities, body-size factors, and environmental responses of the sensory and motor systems, and orientation mechanisms.

"Time and Motion Study for the Foundry"

American Foundrymen's Society, Des Plains, Illinois, 1954, 167 pages, $10.00

Anyone interested in foundry activity and the use of Motion and Time Study in this area should be extremely interested in *Time and Motion Study for the Foundry*. The American Foundrymen's Society has rendered a valuable service to the Industrial Engineers engaged in foundry work. This book hits the highlights and details involved in establishing and maintaining a work measurement program in a specialized work area. Contributing authors include such well-known Industrial Engineers as Phil Carroll, Marvin Mundel, and many others. A good book, if this is your line of work.

"A Million Random Digits"

The Free Press, Glencoe, Illinois, 195 pages, $10.00

It's rather difficult to review a book that contains a million and more numbers with little written material. Each number, however, is a bargain even at the price of $10.00 for the volume—1/1000 of a cent for each. Seriously, this book is an unquestionable bargain if you have need of random numbers. With the current developments in mathematical and statistical analysis, you might need a good set of these values.

"Management in the Home"

by Lillian M. Gilbreth, Orpha Mae Thomas, and Eleanor Clymer; Dodd, Mead and Company, New York, 1954, 241 pages, $3.95

This book on the application of scientific management to home-making makes use of much of the extensive research that has been done in this field. Illustrated with numerous action pictures and charts, it shows the housewife how changes in work methods, equipment, layout, and working conditions can enable her to make the best use of her money, time, and energy. A good book for the Mrs.

"Economic Activity Analysis"

edited by Oskar Morgenstern, John Wiley & Sons, Inc., New York, 1954, 554 pages, $6.75

The studies collected in this volume have been made by the Economics Research Project, Princeton University on "The Mathematical Structure of American Type Economics." They were supported by the Office of Naval Research. The writings fall into the fields of economic activity analysis and linear programming. These works will be useful to the Industrial Engineer interested in input-output analysis, linear programming and the like.

"Operations Research for Management"

edited by Joseph F. McCloskey and Florence N. Trefethen, The John Hopkins Press, Baltimore 18, Maryland, 1954, 416 pages, $7.50

I would highly recommend this book to every Industrial Engineer. The authors have done a fine job in adding coherence to the areas now being called Operations Research. However, the Industrial Engineer is likely to feel that the authors know nothing of Industrial Engineering analysis. This does seem to be the case. The book could have been an even greater contribution if the authors, and the "Operations Researcher" in general, would take advantage of the constructive work being done in Industrial Engineering rather than insist that their work is entirely different and better. Both activities have much in common, and tend to work toward similar obpectives.

"Engineering Analysis"

by D. W. VerPlanck and B. R. Teare, Jr., New York; John Wiley and Sons, Inc., 1954, 344 pages, $6.00.

Only an exceptional collegiate text usually can stir a practitioner's enthusiasm. *Engineering Analysis* is such an exception. Although it is an important contribution to fundamental engineering philosophy and method, it is not surprising since the authors have been more than twenty years in developing the material through their classes and their research at Carnegie Tech. It is not written especially for Industrial Engineers, but the reviewer particularly recommends it to them because of its emphasis on and effective presentation of basic philosophy and method which are so often lacking in both industrial engineering curricula and practice.

The authors' thesis, "professional method" is developed carefully and systematically by solving a progression of increasingly general problems ranging over virtually the whole of the engineering domain. The power of the method is emphasized by the fact that it is applied with equal facility to this wide range of topics. Thus, in reading this text one is forced to realize again that engineering may be more correctly characterized by a "method," rather than just by a subject matter or class of problems and that distinction between "branches" of engineering is both artificial and often restrictive.

Some of the particular values to Industrial Engineers might include the following concepts. The professional method in broadest terms involves a systematic method for (1) recognizing and defining the problem to be solved, (2) planning a way to solve the problem, (3) executing the solution plan, (4) checking the work involved in the solution, and (5) learning and generalizing from what was done. Emphasis is given to the proper role of mathematics in solution of engineering problems through a section on "translation into mathematics." For example in the text, "thus mathematics has inestimable power for increasing your capacity for making logical deductions from a set of facts, but it can not supply the facts nor can mathematics distinguish between right facts and wrong ones, . . . to be useful the original formulation must be a true expression of the right facts."

Through the philosophy and methods presented in the text, two important developments could take place in industrial engineering. Firstly, the motion and process analysis procedures which are now the basis of so much "industrial engineering' could be replaced by truly professional-level engineering; secondly the notion that when the professional-level engineering methods involving mathematics are used, industrial engineering becomes "operations research" could forever be put to rest. Hence, the values of the text with which we are concerned here are (1) in helping practicing industrial engineers to refine and improve the power of their professional methods, and (2) as an advanced undergraduate text for integrating the engineering method for all engineering students, including industrial engineers.—*M. E. Salveson*

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c. An appreciation of the 12 significant trends in material handling—their implications and applications.

d. Theory of space utilization, space layout, order picking, space control, and the design of storage aids.

e. Design of shipping and receiving facilities.

f. Organization and control of material handling activities.

g. . . . and many details on handling specific objects, etc.

Where can a man accumulate this background?

Certainly, it will take many *years* to do this on the job. Even then, no one firm ever covers the whole field. However, there is an answer—

- **The Second Annual Material Handling Training Conference; June 19—July 2, Lake Placid Club, Essex County, N. Y., covers just these things. It is a *systematic training course*—intensive and comprehensive. It will equip your man with a thorough material handling background.**

A number of Chief Industrial Engineers are sending us promising I.E.'s to be trained as handling specialists, or they are coming themselves.

The faculty consists of 18 nationally-known experts. The class is strictly limited to 25. At this writing only eight vacancies were available. If you are interested, we suggest you wire or call us at once.

Director, MHTC
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Lexington, Mass.